Technical Report REMR-CS-56
February 1998

US Army Corps
of Engineers
Waterways Experiment
Station

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Evaluation of Grouting Materials for Anchor Embedments in Hardened Concrete

by Willie E. McDonald

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Prepared for Headquarters, U.S. Army Corps of Engineers

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	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

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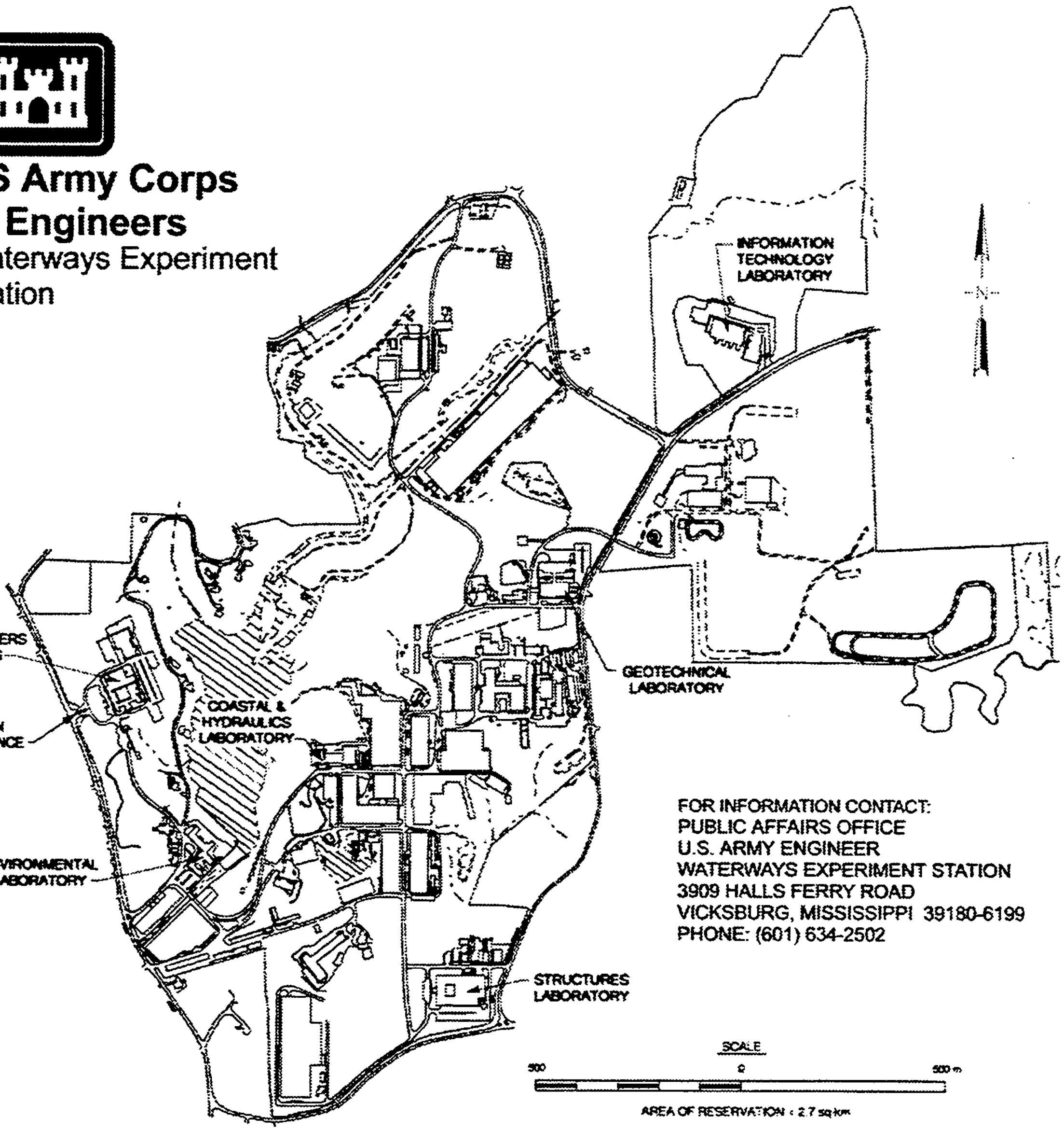

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Contents

Preface

The study reported herein was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Civil Works Research Work Unit 32636, "New Concepts in Maintenance and Repair of Concrete Structures," for which Mr. James E. McDonald, Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), is the Principal Investigator. This work unit is part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program sponsored by HQUSACE. Mr. McDonald is the Problem Area Leader.

The REMR Technical Monitor is Mr. M. K. Lee (CECW-EG), HQUSACE. Dr. Tony C. Liu (CERD-C) is the REMR Coordinator at the Directorate of Research and Development, HQUSACE. Mr. Harold C. Tohlen (CECW-O) and Dr. Liu serve as the REMR Overview Committee. Mr. William F. McCleese, WES, SL, is the REMR Program Manager.

The study was performed by the Concrete and Materials Division (CMD). The work was conducted under the general supervision at WES of Mr. Bryant Mather, Director, SL, and Dr. Paul Mlakar, Chief, CMD, and under the direct supervision of Mr. McDonald. This report was prepared by Mr. Willie E. McDonald, CMD.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Robin R. Cababa, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or kelvins[1]
feet	0.3048	metres
inches	25.4	millimetres
kips (force)	4.448222	kilonewtons
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic yard	0.5932764	kilograms per cubic metre
pounds (mass) per square foot	4.882428	kilograms per square metre
square inches	0.0006451	square millimetres

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9) (F - 32). To obtain Kelvin (K) readings, use: K = (5/9) (F - 32) + 273.15.

1 Introduction

Background

Rehabilitation of hydraulic structures usually requires removal of deteriorated concrete and replacement with new concrete. Steel dowels are normally used to anchor the replacement material to the existing concrete. Typically, anchors are installed by (a) drilling a small-diameter hole into the remaining sound concrete, (b) cleaning the hole, (c) inserting a capsule containing polyester or vinylester resin, and (d) spinning the anchor into the hole. Early-age field pullout tests on anchors installed in this manner under dry conditions indicate this to be a satisfactory procedure. However, a number of failures of anchors installed under submerged conditions have been reported. Consequently, a study was initiated as part of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program to evaluate the effectiveness of selected grout systems for embedment of anchors in concrete.

The effectiveness of neat portland-cement grout, epoxy resin, and prepackaged polyester resin in embedding anchors in hardened concrete was evaluated under a variety of wet and dry installation and curing conditions.[1] Beyond 1 day, all pullout strengths were approximately equal to the ultimate strength of the reinforcing-bar anchor when the anchors were installed under dry conditions, regardless of the type of embedment material or curing conditions. With the exception of the anchors embedded in polyester resin under submerged conditions, pullout strengths were essentially equal to the ultimate strength of the anchor when the anchors were installed under wet or submerged conditions. The overall average pullout strength of anchors embedded in polyester resin under submerged conditions was 35 percent less than the strength of similar anchors installed and cured under dry conditions. The largest reductions in pullout strength, approximately 50 percent, occurred at ages of 6 and 16 months. Also, the overall average pullout strength of anchors embedded in polyester resin under submerged conditions was approximately one-third less than the strength of anchors embedded in epoxy resin and portland-cement grout under wet and submerged

[1] J. F. Best and J. E. McDonald, 1990, "Evaluation of polyester resin, epoxy, and cement grouts for embedding reinforcing steel bars in hardened concrete," Technical Report REMR-CS-23, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

conditions, respectively, and cured under submerged conditions. Although the epoxy resin performed well in these tests when placed in wet holes, it should be noted that the manufacturer does not recommend placement under submerged conditions.

Creep tests were conducted by subjecting pullout specimens to a sustained load of 60 percent of the anchor-yield strength and periodically measuring anchor slippage at the end of the specimen opposite the loaded end. After 6 months under load, anchors embedded in portland-cement grout and epoxy resin were installed and tested under dry conditions and exhibited very low anchor slippage, averaging 0.003 and 0.002 cm (0.0013 and 0.0008 in.), respectively. Under similar conditions, slippage of anchors embedded in polyester resin was approximately 30 times higher. Results of creep tests on specimens fabricated and tested under wet conditions followed a similar trend. The average slippage for anchors embedded in portland-cement grout and epoxy resin was 0.007 and 0.008 cm (0.0028 and 0.0033 in.), respectively, or two to four times higher than results under dry conditions. Anchors embedded in polyester resin, installed, and cured under submerged conditions exhibited significant slippage; in fact, in one case the anchor pulled completely out of the concrete after 14 days under load. After 6 months under load, the two remaining specimens exhibited an average anchor slippage of 0.219 cm (0.0822 in.), approximately 30 times higher than anchors embedded in portland-cement grout under the same conditions.

A 1987 review of available manufacturers' literature on concrete anchor grouting systems revealed that a vinylester resin, prepackaged in glass capsules, was being promoted for use under submerged conditions. According to the manufacturers' representatives, the performance of anchors embedded in vinylester resin under submerged conditions was similar to that of comparable anchors installed in the dry. Since no test data were furnished to substantiate this claim, the U.S. Army Engineer District (USAED), New Orleans, initiated testing by the U.S. Army Engineer Waterways Experiment Station (WES) to evaluate the performance of anchors embedded in vinylester resin under dry and submerged conditions.[1]

Anchors were 3.15-cm- (1-1/4 in.-) diam threaded rods installed in holes drilled to depths of 30.5 and 38.1 cm (12 and 15 in.) with a 3.81-cm- (1-1/2-in.-) outside-diameter core barrel. Pullout tests were conducted at four different ages ranging from 1 to 28 days. Results of pullout tests on anchors installed in dry holes (38.1-cm (15-in.) embedment length) were remarkably consistent with an overall average tensile capacity of 724 MPa (105 kips) at 0.254-cm (0.1-in.) displacement and an average ultimate load of approximately 862 MPa (125 kips), which is near the yield load of the anchors. In comparison, results of pullout tests on anchors installed under submerged conditions were relatively erratic, with an overall tensile capacity of 248 MPa (36 kips) at 0.254-cm (0.1-in.) displacement and an average ultimate load of 331 MPa (48 kips). Obviously, the tensile load

[1] J. E. McDonald, 1989, "Evaluation of vinylester resin for anchor embedment in concrete," Technical Report REMR-CS-20, U.S. Army Engineer Waterways Experiment, Vicksburg, MS.

capacity of anchors embedded in concrete with vinylester-resin capsules is significantly reduced when the anchors are installed under submerged conditions. At a displacement of 0.254 cm (0.1 in.), the tensile capacity of anchors embedded under submerged conditions was approximately one-third that of similar anchors embedded in dry holes.

The reduced tensile capacity of anchors embedded in concrete under submerged conditions with prepackaged polyester-resin and vinylester-resin cartridges was primarily attributed to the anchor installation procedure. Resin extruded from dry holes during anchor installation was very cohesive, and a significant effort was required to obtain the full embedment depth. In comparison, anchor installation required significantly less effort under submerged conditions. Also, the extruded resin was much more fluid under wet conditions, and the creamy color contrasted with the black resin extruded under dry conditions. Although insertion of the adhesive capsule or cartridge into the drill hole displaces the majority of the water in the hole, water will remain between the walls of the adhesive container and the drill hole. Insertion of the anchor traps this water in the drill hole and causes it to become mixed with the adhesive, resulting in an anchor with reduced tensile capacity.

Subsequent tests on anchors embedded in vinylester under submerged conditions[1] indicated that increasing the embedment length from 30.48 to 60.96 cm (12 to 24 in.) resulted in a 60-percent increase in tensile capacity at 0.254-cm (0.1-in.) displacement. However, this increased tensile capacity of anchors installed under submerged conditions was still only about one-half the load capacity of anchors with 30.48-cm (12-in.) embedment lengths installed in dry holes. While it may be possible to improve anchor performance under submerged conditions by further increasing embedment lengths, significant additional material and labor costs are associated with increasing embedment lengths of anchors in concrete. Therefore, the development of improved anchor installation procedures which do not require excessive embedment lengths was necessary.

An anchor-installation procedure that eliminates the problem of resin and water mixing in the drill hole is described by McDonald (1990).[1] In the revised installation procedure, a small volume of adhesive was injected into the bottom of the drill hole in bulk form prior to insertion of the adhesive capsule. This injection was easily accomplished with paired plastic cartridges which contained the vinylester resin and a hardener. The cartridges were inserted into a tool similar to a caulking gun which automatically dispensed the proper material proportions through a static mixing tube directly into the drill hole. Once the injection was completed, insertion of a prepackaged vinylester-resin capsule displaced the remainder of the water in the drill hole prior to anchor insertion and spinning.

[1] J. E. McDonald, 1990, "Anchor embedment in hardened concrete under submerged conditions," Technical Report REMR-CS-33, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Anchors with 38.1-cm (15-in.) embedment lengths installed with the revised procedure exhibited essentially the same tensile capacity under dry and submerged conditions. At 0.254-cm (0.1-in.) displacement, the tensile capacity of vertical anchors installed with the revised procedure under submerged conditions averaged more than three times greater than that of similar anchors installed with the original procedure. Also, the ultimate tensile capacity of anchors installed under submerged conditions with the revised procedure averaged more than 897 MPa (130 kips) compared to an average ultimate capacity of less than 345 MPa (50 kips) for similar anchors installed with the original procedure.

Horizontal anchors installed with the revised procedure under both dry and submerged conditions also exhibited excellent tensile load capacities. Overall, the difference in tensile capacity between horizontal anchors installed under dry and submerged conditions was less than 2 percent at 0.254-cm (0.1-in.) displacement. Similarly, the average difference in tensile capacity between horizontal and vertical anchors was only 3 and 5 percent for anchors installed under submerged and dry conditions, respectively.

Based on the results of these tests, it was concluded that the two-step anchor installation procedure should be followed when prepackaged polyester resin or vinylester resin is to be used as an embedment material for short (less than 38.1-cm (15-in.) embedment length) steel anchors in hardened concrete under submerged conditions. A further conclusion was that the two-step installation procedure may not be necessary for rock anchors which normally have longer embedment lengths.

With the development of disposable coaxial or paired cartridges, epoxy grouts became available for anchor embedment in hardened concrete. According to suppliers, these developments made it possible to inject all of the embedment material, thus eliminating the need for the second step in the two-step installation procedure. Also, it was claimed that anchors embedded in epoxy should perform much better than other commonly used materials, particularly under submerged conditions and sustained loads. Consequently, additional anchor tests were initiated to evaluate these claims.

Objective

The objective of this experimental program was to evaluate the effectiveness of selected materials and procedures for embedment of anchors in hardened concrete under dry and submerged conditions.

Scope of Work

Two epoxies, a vinylester and a cementitious grout, were used for anchor embedment in hardened concrete under dry and submerged conditions. Three

anchors (No. 6 reinforcing bars) were installed for each evaluation condition. Pullout tests were conducted at 1, 3, 7, 28, and 365 days following anchor installation. Creep tests were initiated at 7 days by subjecting pullout specimens to a sustained load of 60 percent of the anchor-yield strength. Anchor slippage at the end of the specimen opposite the loaded end was measured periodically during the 6-month loading period.

2 Evaluation Program

Test Specimens

A total of 12 concrete blocks were fabricated and represented the base concrete for anchor installations. Recesses on the top surfaces of six of these concrete blocks were provided to pond water, thereby simulating submerged conditions (Figures 1 and 2). Twelve holes were predrilled into each concrete block using a Hilti impact hammer drill and carbide tip bits to accommodate installation of anchor specimens. The diameters and depths of the holes were drilled in accordance with recommended manufacturers' specifications for each respective adhesive product (Figure 3). A total of twenty-four 15.24- by 15.24- by 45.72-cm (6- by 6- by 18-in.) concrete beams were fabricated to represent the base concrete for anchor installations in creep tests. One percussion hole was predrilled into each concrete beam in accordance with the same recommended specifications for anchor installations in the concrete blocks. A conventional 21-MPa (3,000-psi) concrete mixture (limestone aggregate) was used for fabrication of the concrete blocks and concrete beams. Anchor specimens consisted of standard A36 No. six 1.91-cm (3/4-in.-diam) reinforcement steel bars.

Adhesive Products and Anchor Installations

A total of 144 anchor specimens were installed for pullout testing and a total of 24 anchor specimens were installed for creep testing. One-half of the anchor specimens were installed in dry conditions and one-half were installed in submerged conditions for both pullout and creep testing. Prior to dry installation of the anchor specimens, the predrilled holes were air blown and cleaned with a nylon brush to rid them of dust and loose particles. The same procedure was followed for submerged installations. For submerged anchor installations, water was ponded for a period of 2 weeks prior to anchor installations to allow the saturation of the holes.

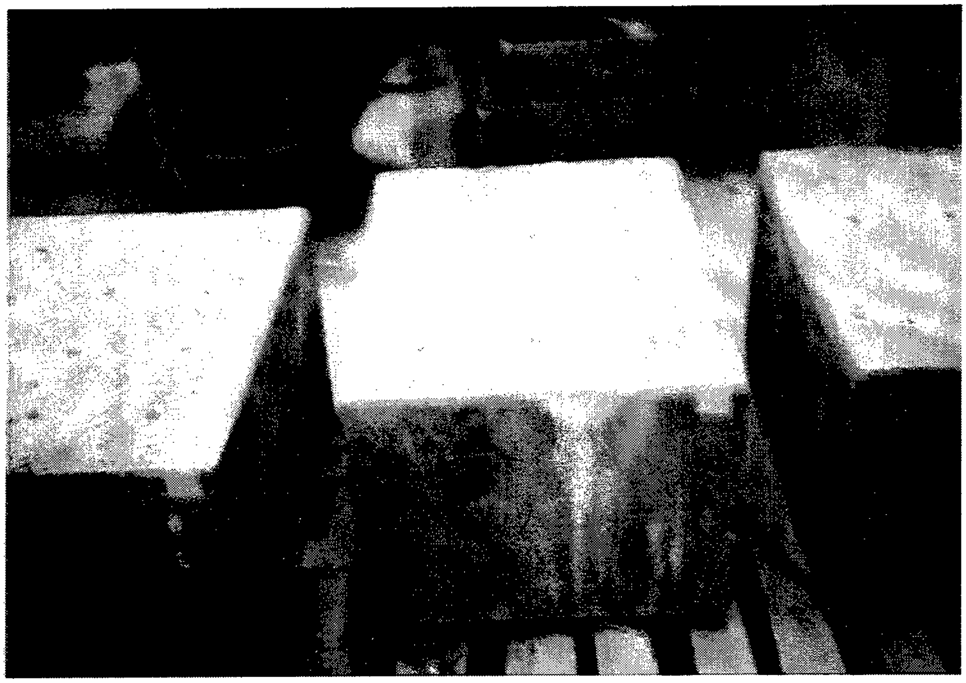


Figure 1. Typical fabricated concrete blocks for dry anchor installations

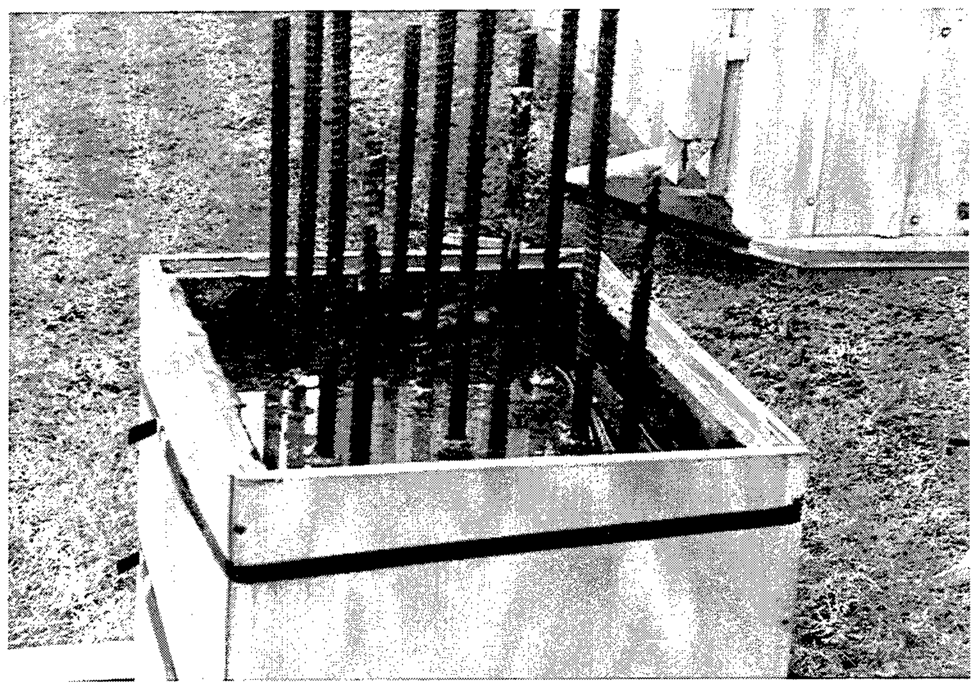
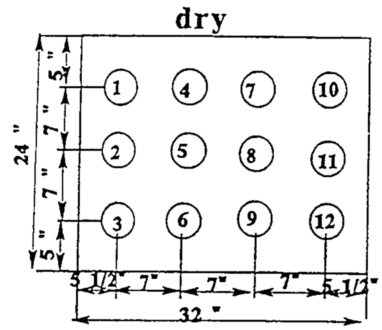


Figure 2. Typical fabricated concrete blocks for submerged anchor installations

dry test blocks

matl type	hole no.	hole diam.	embed depth
anchor-it	1,2,3	7/8	8-3/4
hva/c100	4,5,6	1	6 5/8
epcon	7,8,9	7/8	6-3/4
c100	10,11,12	7/8	6 5/8



underwater test blocks

matl type	hole no.	hole diam.	embed depth
anchor-it	1,2,3	7/8	6-1/2
hva/c100	4,5,6	1	6 5/8
epcon	7,8,9	7/8	6-3/4
lokset	10,11,12	1-1/4	12

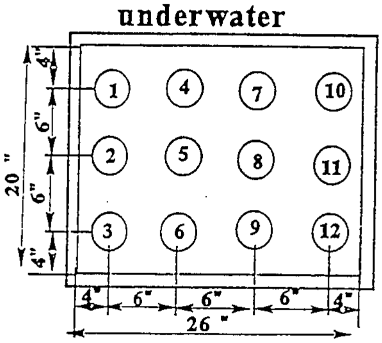


Figure 3. Diameter and depth specifications for anchor installations corresponding to each adhesive product (U.S. dimensions are in inches)

The adhesive products used in this test study were designated as Adhesives A, B, C, D, and E. Each adhesive product and procedures for anchor installations are described.

Adhesive A (Epcon), manufactured by ITW Ramset, is a two-component ceramic-filled epoxy adhesive (Figure 4). The product is contained in a two-chambered cartridge consisting of epoxy and hardener components in separate chambers. The components are blended by static mixer elements contained within a nozzle system and is light gray in color when dispensed using a hand-operated caulking-type gun. Anchors installed with Adhesive A were embedded in 2.22-cm- (7/8-in.-) diam holes to a depth of 17.45 cm (6-3/4 in.) for dry and submerged installations. The holes were filled to one-half the hole depth by inserting a dispenser nozzle to the bottom of the hole and slowly withdrawing the nozzle as the adhesive filled the hole. The anchors were inserted immediately afterwards and slowly pushed to the bottom of the holes with a clockwise/counterclockwise rotational motion, displacing the adhesive to the top of the hole.

Adhesive B (Anchor-It), manufactured by Adhesive Technology Corporation, is a light paste epoxy adhesive filled with superfine aggregates and hardener components (Figure 5). The proportioned components contained in coaxial cartridges are blended in a static mixing nozzle when applied with using an

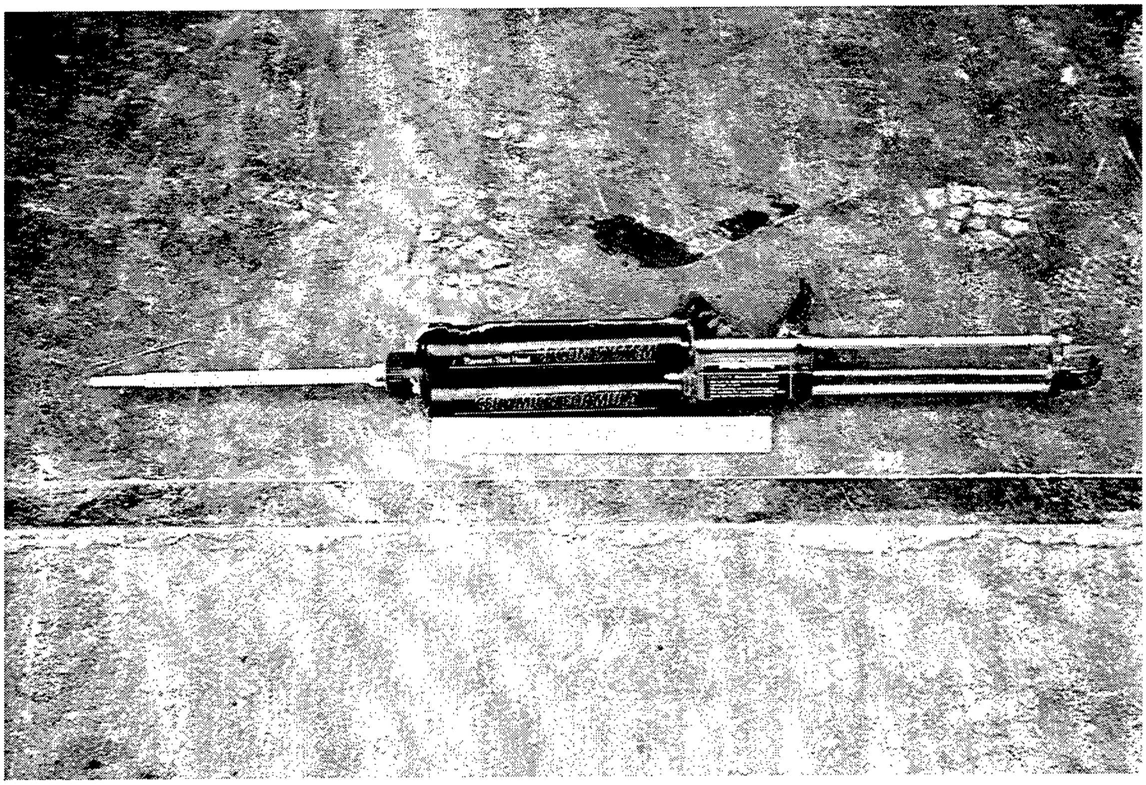


Figure 4. Adhesive A - representative epoxy adhesive

Figure 5. Adhesive B - representative epoxy adhesive

air-powered pneumatic dispenser. The adhesive is concrete gray in color, and a hand operated caulking-type gun can also be used. Anchors installed with Adhesive B were embedded in 2.22-cm- (7/8-in.-) diam holes at depths of 22.23 and 27.94 cm (8-3/4 and 11 in.), respectively, for dry and submerged installations. Following the manufacturer's recommendation for submerged anchor installations, Adhesive B was heated to 80 °F prior to anchor installations to compensate for the anticipated reduction in set time for submerged conditions. Apparently, heating the adhesive slows down the reaction process. Procedures for cleaning of holes and anchor installations with Adhesive B are the same as described for Adhesive A.

Adhesive C (HEA capsule/C100), products of Hilti Corporation, represents the combined application of two vinylester resins for anchor installations (Figure 6). HEA is a multicomponent vinylester resin contained in a 1.91- by 16.83-cm (3/4- by 6-5/8-in.) dual glass vial capsule (other sizes are available) and consists of quartz sand, a benzol peroxide hardening agent, and the vinylester resin. C100 is a two-component vinylester resin packaged in a two-chambered plastic cartridge with the polyester/silica resin and dibenzol peroxide hardener components in separate chambers. The components are blended by static mixer elements within a nozzle attachment when dispensed using a hand-operated caulking-type gun. Following previously described hole cleaning procedures, anchor specimens installed with Adhesive C were embedded in percussion holes

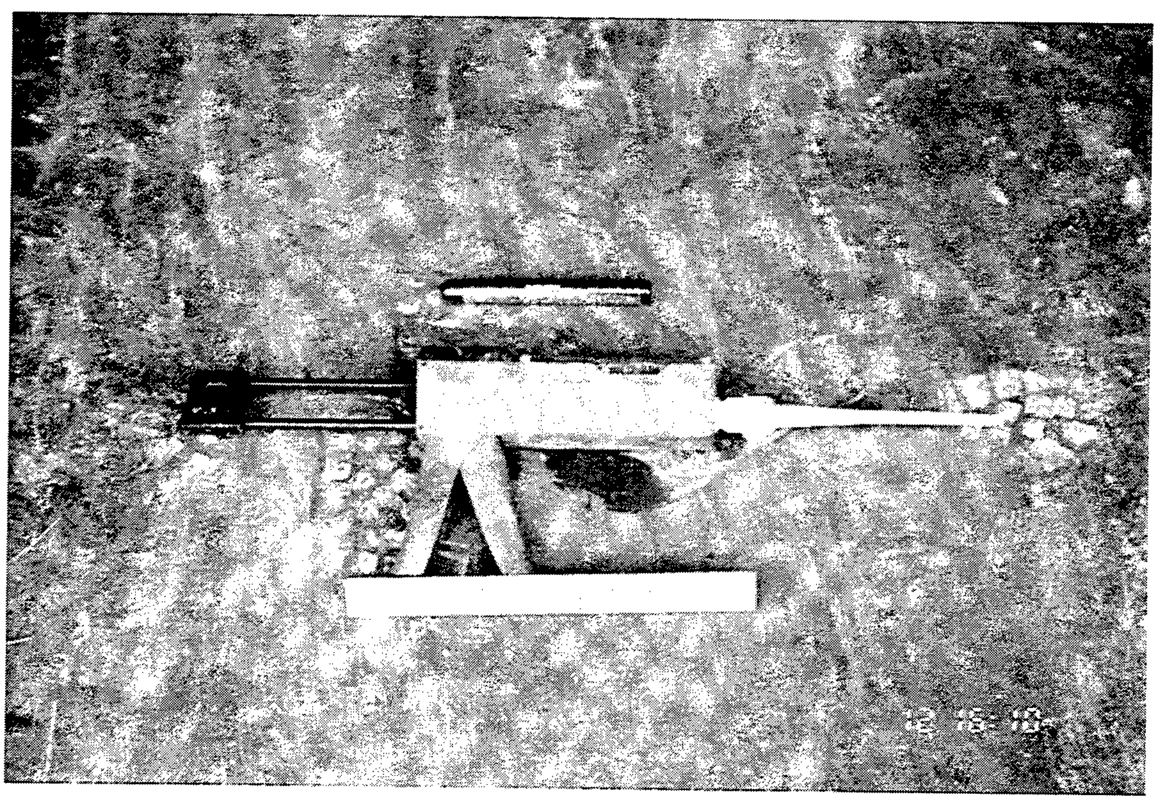


Figure 6. Adhesive C - representative vinylester resins - C100 and HEA

2.54 cm (1 in.) in diameter and 16.83 cm (6-5/8 in.) in depth for both dry and submerged installations. The C100 resin was first dispensed to about one-half of the hole depth followed by insertion of the HEA capsule. Insertion of the HEA capsule displaced the C100 resin to the top of the hole. An anchor setting tool attachment for an electric drill was used to spin the anchors into the hole. This process resulted in both breaking the HEA glass capsule and mixing of the resin components.

Although the combined application of both the C100 and HEA capsule was used to install anchor specimens in dry and submerged conditions, the primary advantage is for submerged installations. The C100 displaces the water that normally becomes trapped between the walls of the HEA capsule and the hole when the HEA adhesive is used alone for submerged applications. The trapped water in the holes mixes with the HEA resin and, as a result, weakens the bonding capacity. Application of Adhesive C for submerged anchors was devised by Hilti and WES and described in previous evaluation studies (McDonald 1989).[1]

Adhesive D (C100), manufactured by Hilti Corporation, is described above. As a result of strong manufacturers' recommendation against the use of C100 resin alone for submerged applications, the C100 resin was included singularly only for dry anchor installations. Anchor specimens installed using Adhesive D were embedded in 2.22-cm-diam by 16.83-cm- (7/8-in.-diam by 6-5/8-in.-) depth drilled holes. Again, procedures for cleaning the holes and installing the anchor using Adhesive D followed those procedures described for Adhesive A.

Adhesive E (Lokset), manufactured by Forsoc International Unlimited, is a cementitious compound encased in a special plastic wrapping which, when immersed in water, will allow control wetting of the contents to form a thixotropic grout (Figure 7). The adhesive is packaged in a cellophane-type sausage-shape cartridges designed for insertion into a range of hole sizes. Following normal hole cleaning procedures, the cartridge is immersed in water for 300 to 900 sec (5 to 15 min) and reaction of the components occurs when the cartridge is ruptured by insertion of the anchor. Adhesive E is manufactured specifically for underwater anchor installations. The cartridges were inserted into 2.54-cm-diam by 30.48-cm- (1-in.-diam by 12-in.-) depth drilled holes. The anchor specimens were forced into the holes through the cartridges and rotated to initiated the chemical bonding process.

Testing Equipment and Procedures

Pullout test loads were applied by a hollow-core hydraulic ram using hydraulic pressure supplied by an electrically powered pump. The loading system was calibrated by the correlation of voltage outputs (measured by a voltage meter) and loads obtained from a 3,034-MPa (440-kip) universal laboratory testing machine. Digital display of the voltage output allowed the magnitude and rate of loading to

[1] McDonald, 1989, op. cit.

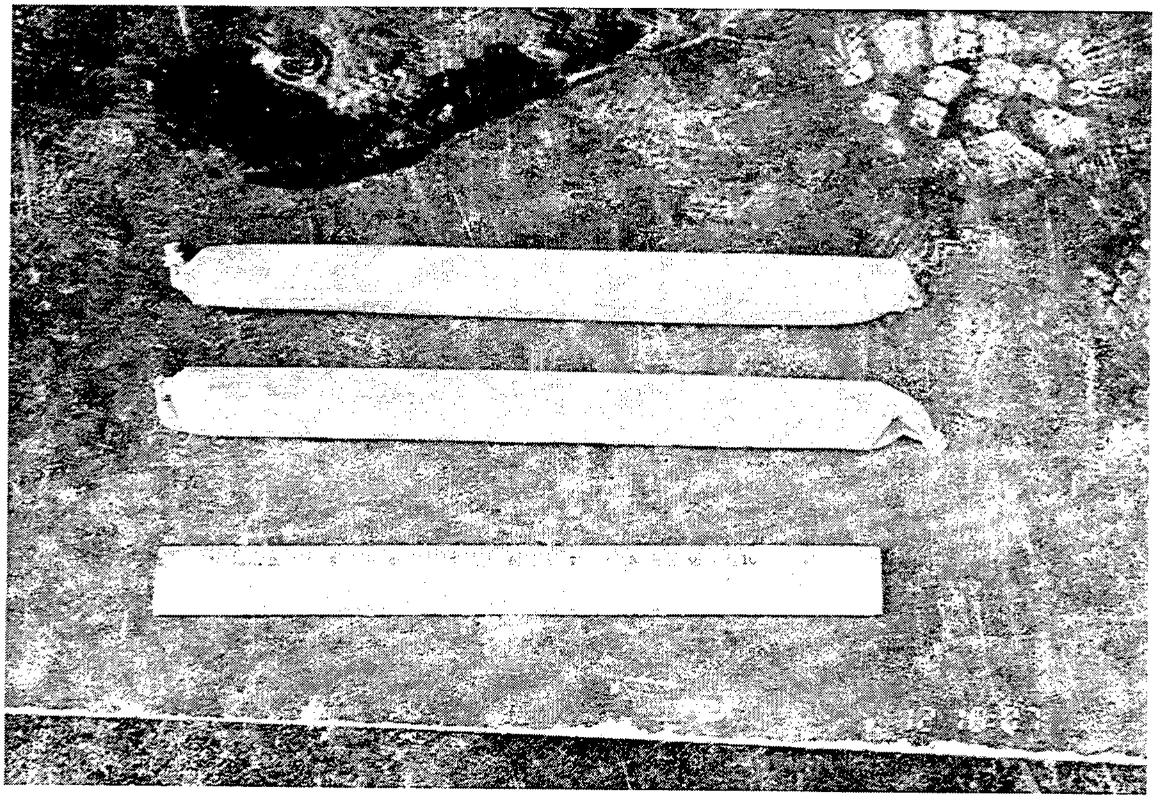


Figure 7. Adhesive E - representative cementitious adhesive

be monitored as well as measured with the voltage meter throughout testing. The hydraulic ram was centered over the anchor specimens and secured by a head and jaw grip assembly. This head and jaw assembly also provided load transfer from the hydraulic ram to the anchor specimens during testing. A linear variable differential transformer (LVDT) gauge was placed on the top surface of the exposed end of the anchor specimens to measure displacements of the anchors relative to the surface of the concrete blocks as shown in Figure 8. Continuous measurements of load and displacements throughout testing were processed and recorded using an electronic data acquisition/control unit configured in the overall system. The loading rate for all pullout tests was maintained at approximately 21 MPa (3 kips) per minute.

Long-term creep strain test loads were applied by a calibrated hydraulic ram and supply pump setup similar to the setup used for pullout tests described previously, without the data acquisition/control unit. The lower ends of the concrete beams were saw cut at depths specified for anchor embedments to expose the ends of the anchors opposite the loaded ends. This allowed anchor displacements to be measured by positioning a mechanical dial gauge extensometer on the top of the exposed surface of the anchors (Figure 9). The anchor specimens were loaded 7 days after embedment under a sustained load of 60 percent of the yield strength of the anchors. Slip deflections were measured periodically during the 6-month test period.

Figure 8. Typical setup for pullout tests

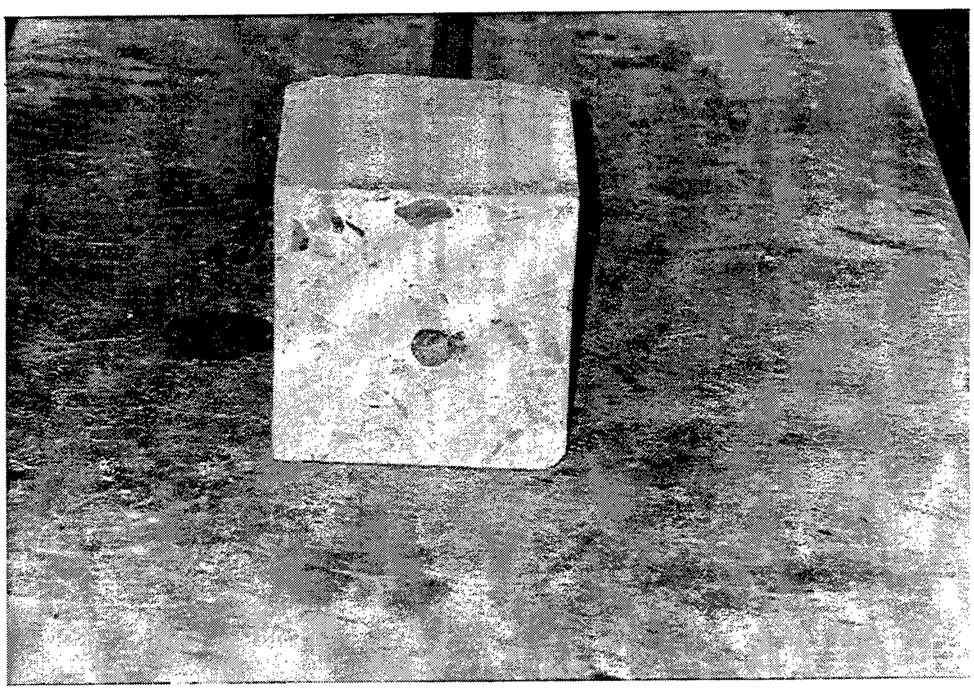


Figure 9. Typical view of opposite end for creep specimens

3 Test Results and Discussions

Pullout Tests

Introduction

Results of pullout tests on dry and submerged anchor installations bonded by the representative adhesive products are summarized in Appendix A, Tables 1 through 8. These results correspond with 1-, 3-, 7-, 28-, and 365-day maturity ages for testing of anchors following installations. The basis for comparisons of anchor performances is given by tensile load capacities as pullout loads at 0.254- and 0.508-cm (0.1- and 0.2-in.) displacements and also maximum loads.[1]

Adhesive A (epoxy)

For dry anchor installations bonded by Adhesive A, the maximum average tensile load capacities attained were approximately equal to the ultimate strength of the anchors 290 MPa (42 kips) with the exception of early-age, 1-day anchors. Here, the average tensile capacity attained was about one-half the anchor's ultimate strength. However, in pullout tests for submerged anchor installations, very poor performances were characterized by erratic, inconsistent, and low tensile load capacities. By comparisons, very significant differences were typical for performances of dry versus submerged installations with substantially lower tensile load capacities for the submerged installations (Figures 10 through 14). Dry anchor installations attained an average of two and one-half to eight times greater tensile capacities than submerged installations. Dry versus submerged anchor performances at displacements of 0.254 and 0.508 cm (0.1 and 0.2 in.) are shown in Figures 15 and 16, respectively.

Since these results contrasted significantly from manufacturer's specifications, a representative for the manufacturer of Adhesive A was consulted and an onsite

[1] McDonald, 1990, op. cit.

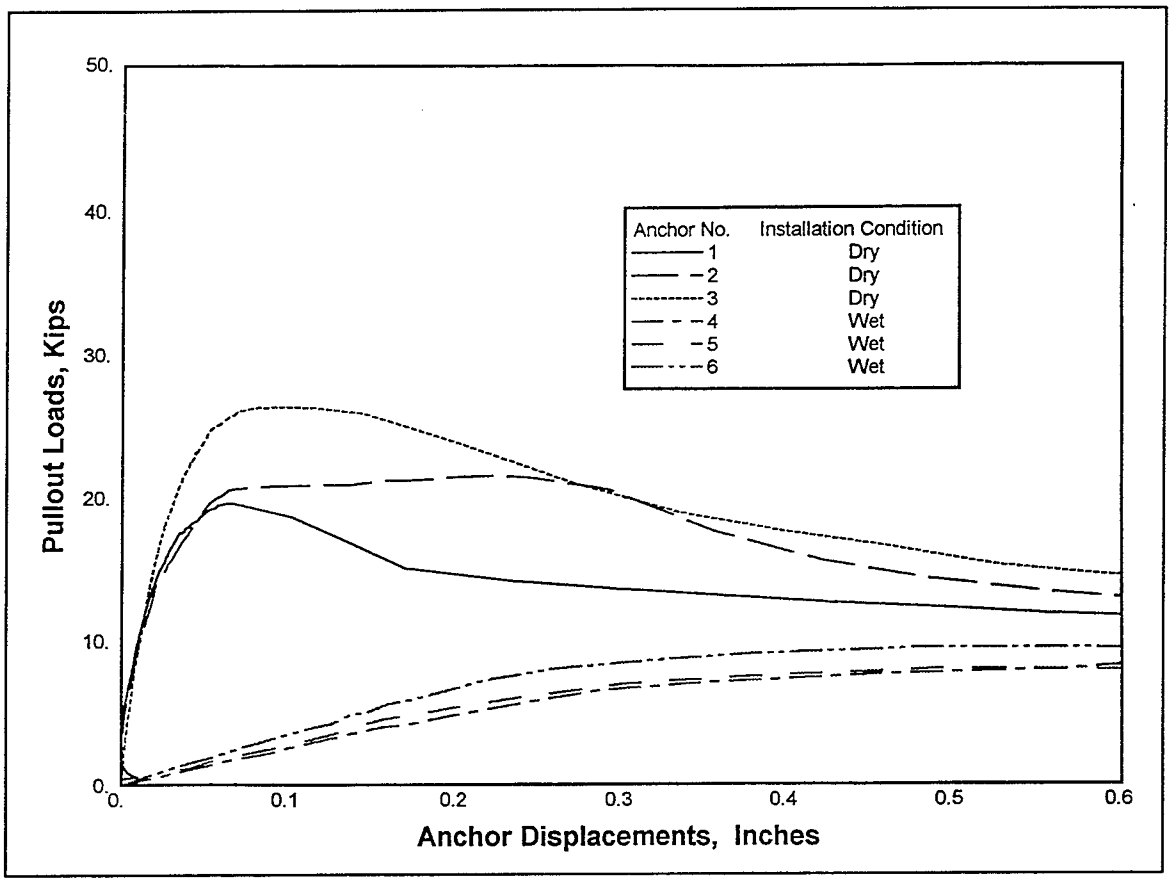


Figure 10. Results of pullout tests conducted at 1 day on anchors bonded by Adhesive A

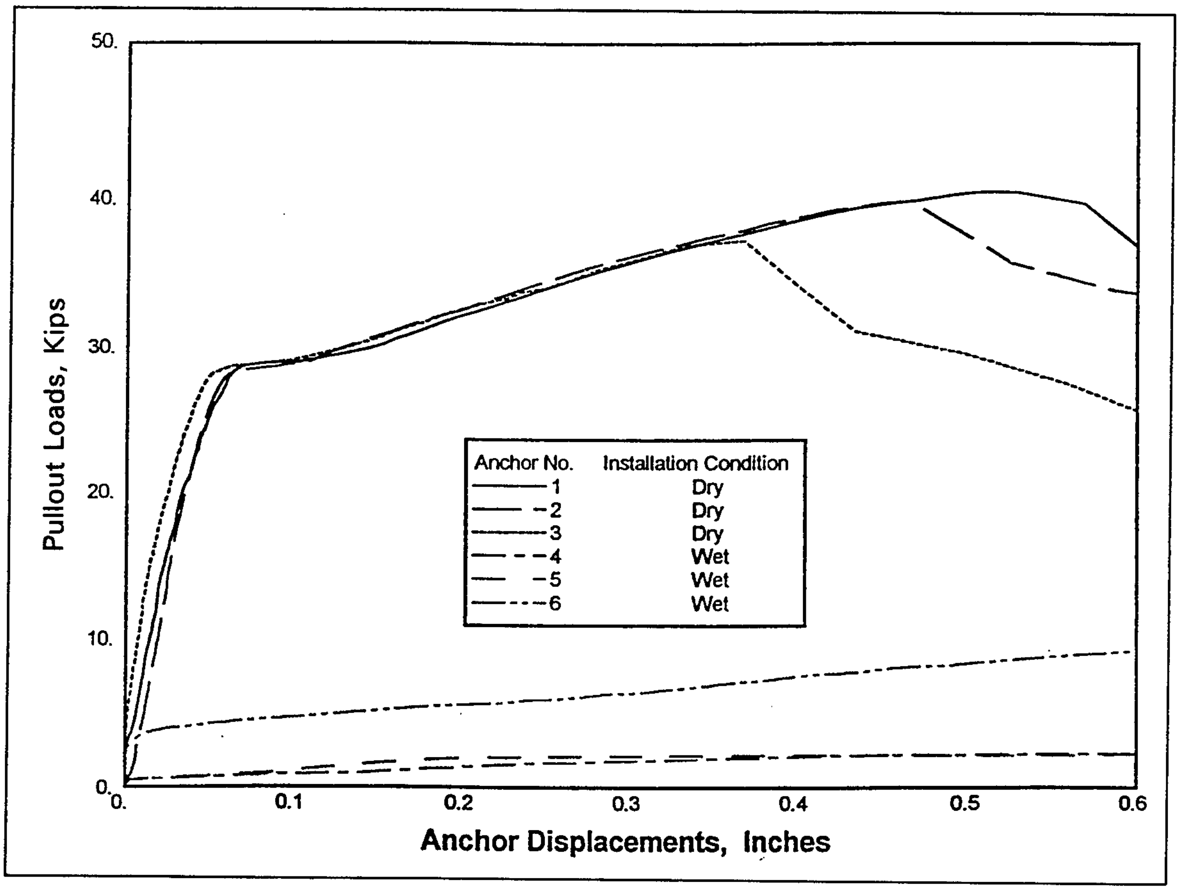


Figure 11. Results of pullout tests conducted at 3 days on anchors bonded with Adhesive A

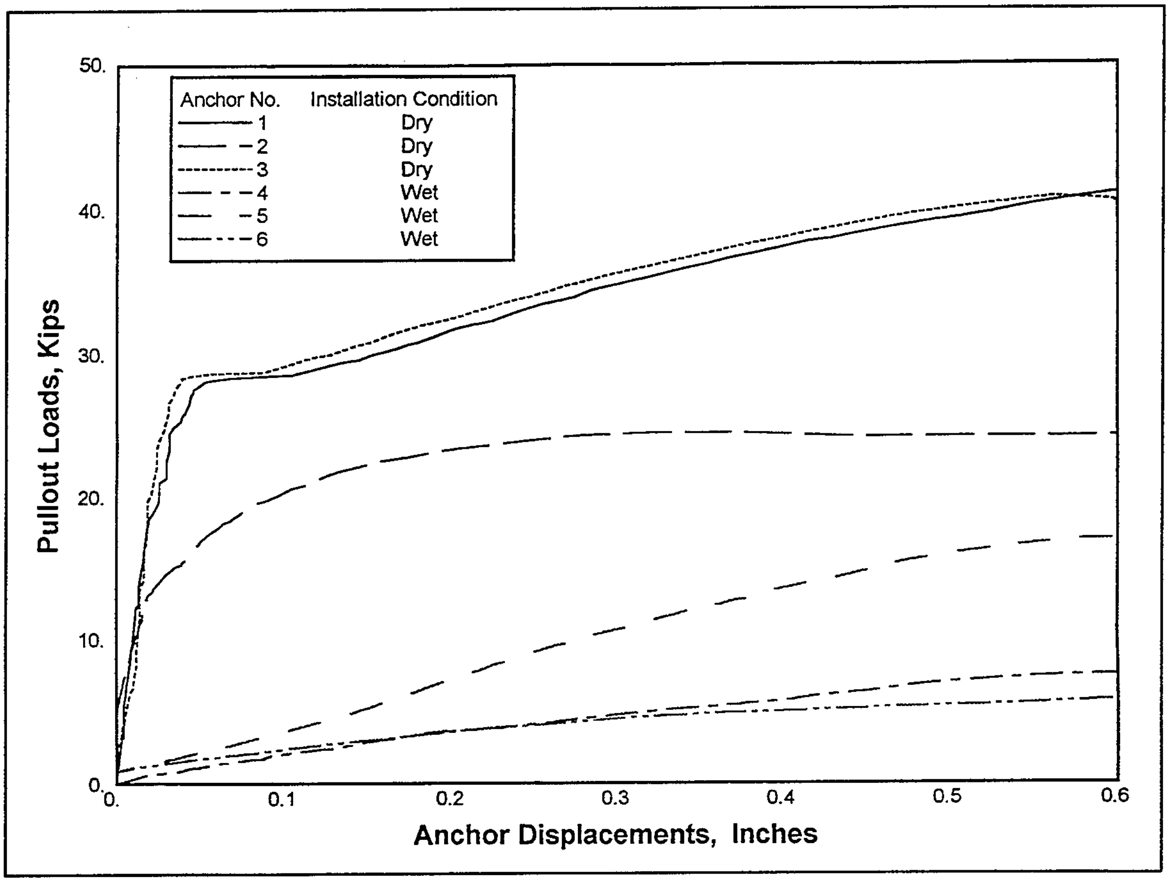


Figure 12. Results of pullout tests conducted at 7 days on anchors bonded with Adhesive A

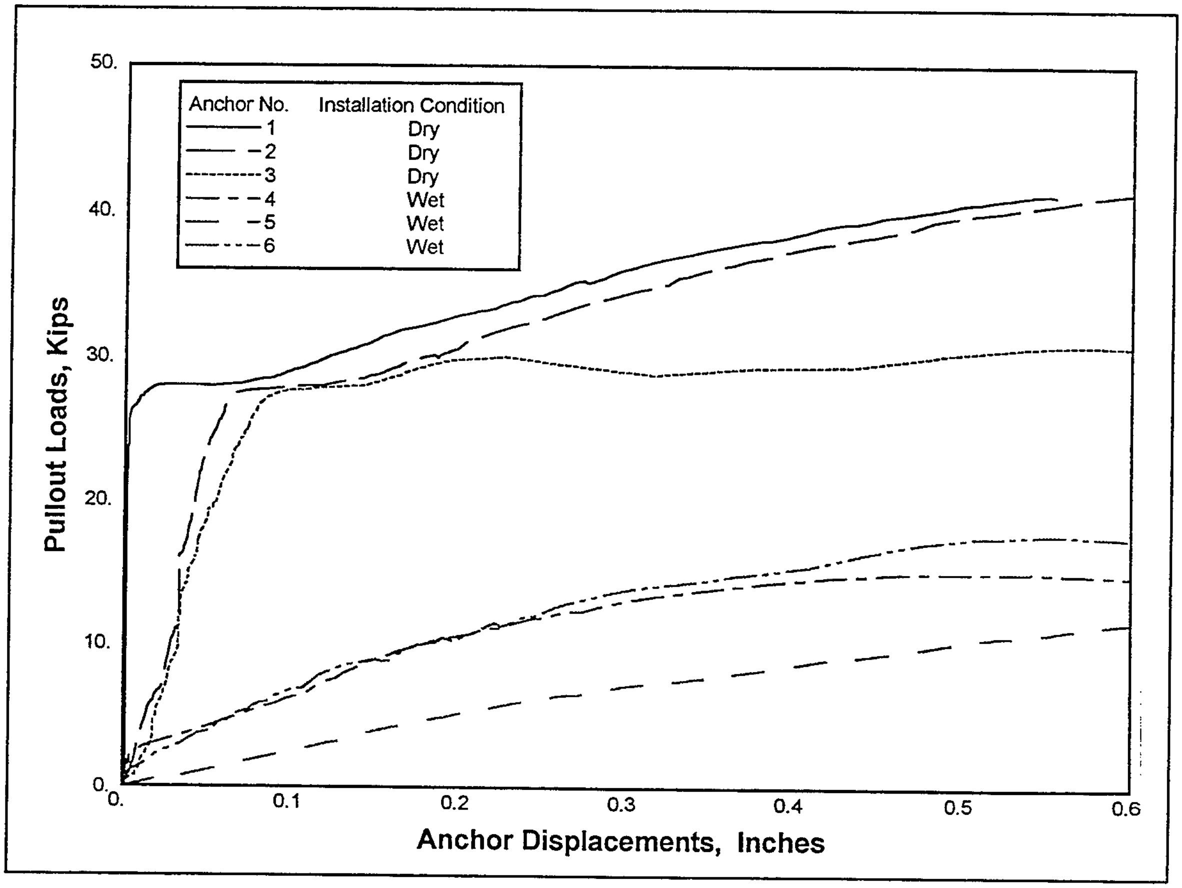


Figure 13. Results of pullout tests at 28 days conducted on anchors bonded with Adhesive A

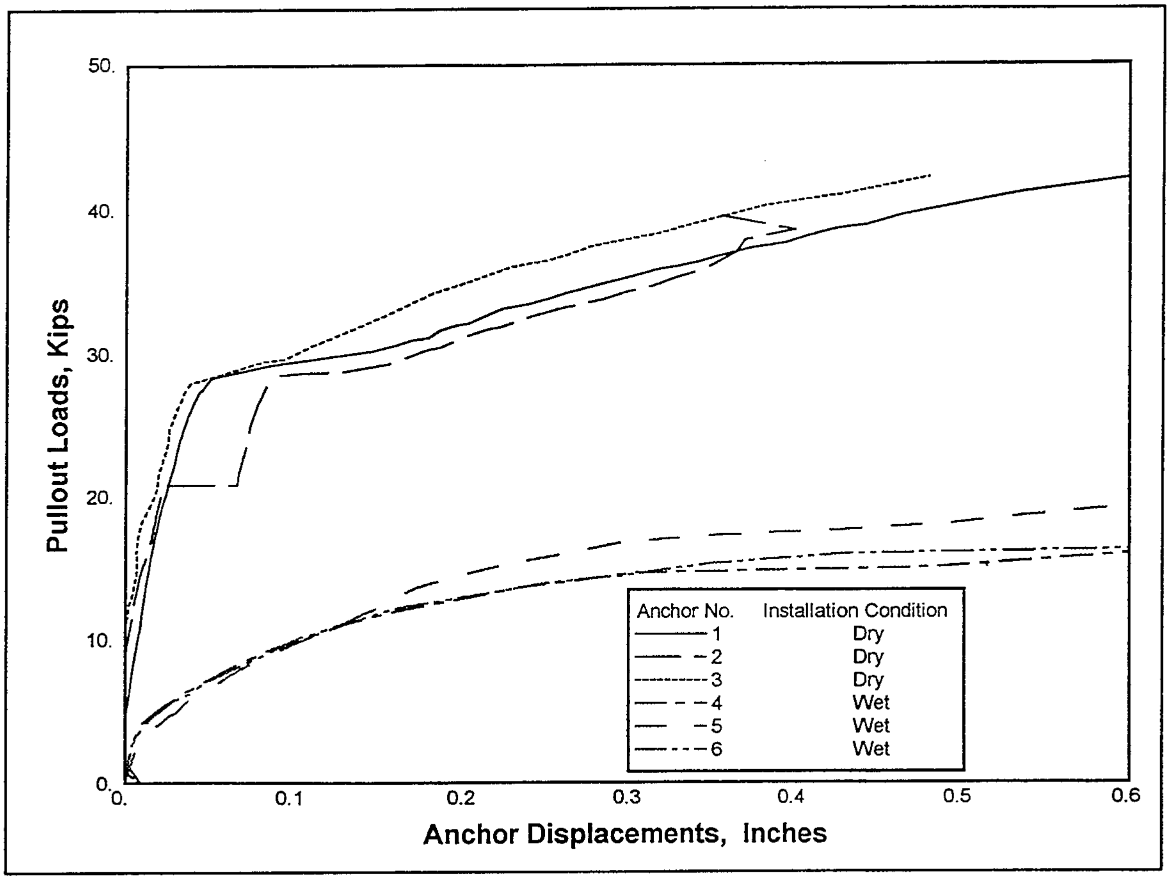


Figure 14. Results of pullout tests at 1 year on anchors bonded with Adhesive A

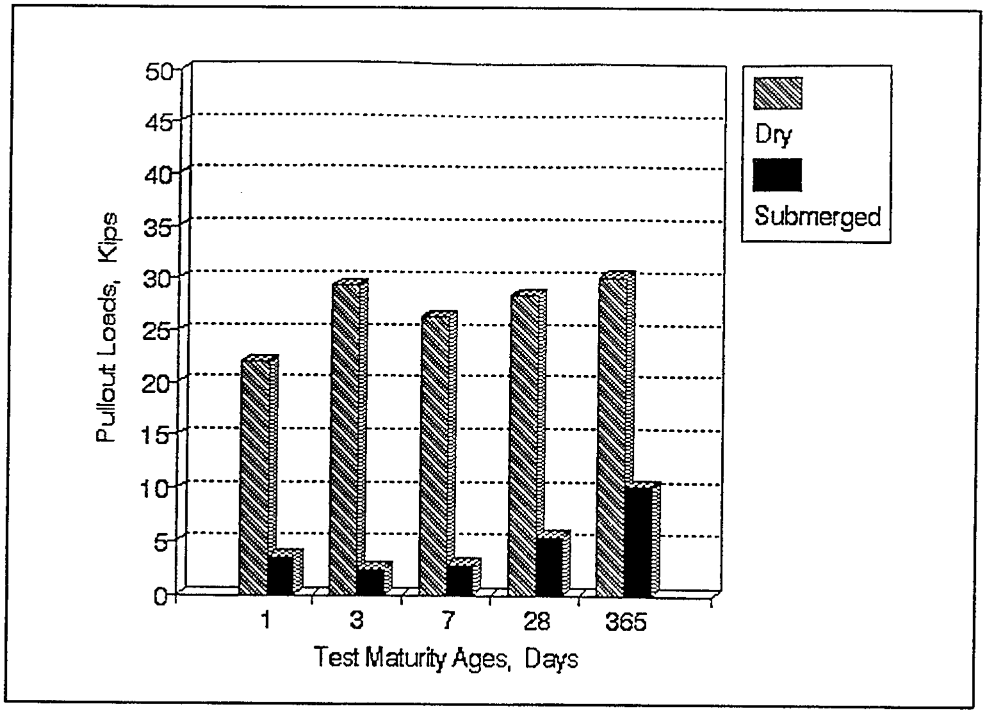


Figure 15. Average tensile capacity at 0.254-cm (0.1-in.) displacements of anchors installed with Adhesive A under dry and submerged conditions

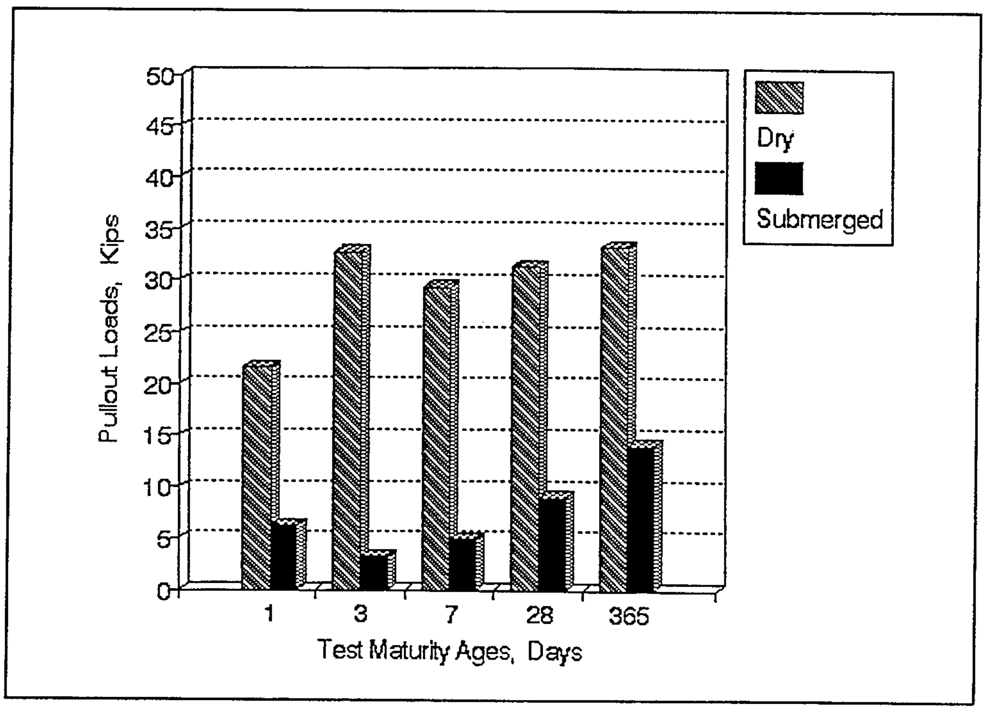


Figure 16. Average tensile capacity at 0.508-cm (0.2-in.) displacements of anchors installed with Adhesive A under dry and submerged conditions

review of laboratory procedures for bonding submerged anchor installations was provided. As a result, only very minor deviations from recommended procedures were noted. Additional submerged anchor installations were accomplished, carefully incorporating the minor procedural changes, and subsequent tests were conducted. Although slightly improved results were obtained, the criteria for 2 weeks of saturation for the holes were not maintained. To determine the effects of hole saturation on the bond properties of Adhesive A, submerged anchors were installed and 3-day tests conducted after 3, 7, 14 days of hole saturation.

The results of the pullout tests for different saturation periods were inconclusive. No definite correlation was indicated between the 3-, 7-, and 14-day saturation periods and the resulting bonding capacity provided by Adhesive A. However, the pattern of erratic and poor performances for submerged anchor installations continued to be demonstrated for each saturation period. These results served to confirm previous tests in which Adhesive A failed to provide adequate bonding capacities for anchor installations under submerged conditions.

Adhesive B (epoxy)

Pullout tests conducted on anchors bonded by Adhesive B followed similar patterns for Adhesive A. Dry installations exhibited tensile capacities within a range of approximately the ultimate strength of the anchors, with the early-age, 1-day, anchors in this case attaining average tensile capacity about 33 percent less than the ultimate anchor strength. Anchor performances for submerged installations were again characterized by inconsistently poor performances of one and one-half to four times less tensile capacities than for dry installations (Figures 17 through 21). Comparisons of dry versus submerged anchor performances at 0.254- and 0.508-cm- (0.1- and 0.2-in.-) displacements for Adhesive B are illustrated in Figures 22 and 23, respectively.

Review of anchor failures for submerged installations with epoxy adhesives A and B indicated a lack of effective bonding between the adhesives and the inner walls of the holes. This is supported by observations of the adhesives remaining physically smooth and intact after failure at the interfaces with the inner walls of the holes (Figure 24). Normally, some fracture of material would be expected as the bonds are broken during failure (Figure 25).

Adhesive C (composite vinylester)

For Adhesive C, anchor performances for dry installations averaged maximum sustained tensile load capacities greater than the ultimate strength of the anchors in each of the tests. However, distinct reductions were exhibited for submerged installations averaging slightly more than one and one-half times lower tensile capacities (Figures 26 through 30). Average pullout loads for dry versus

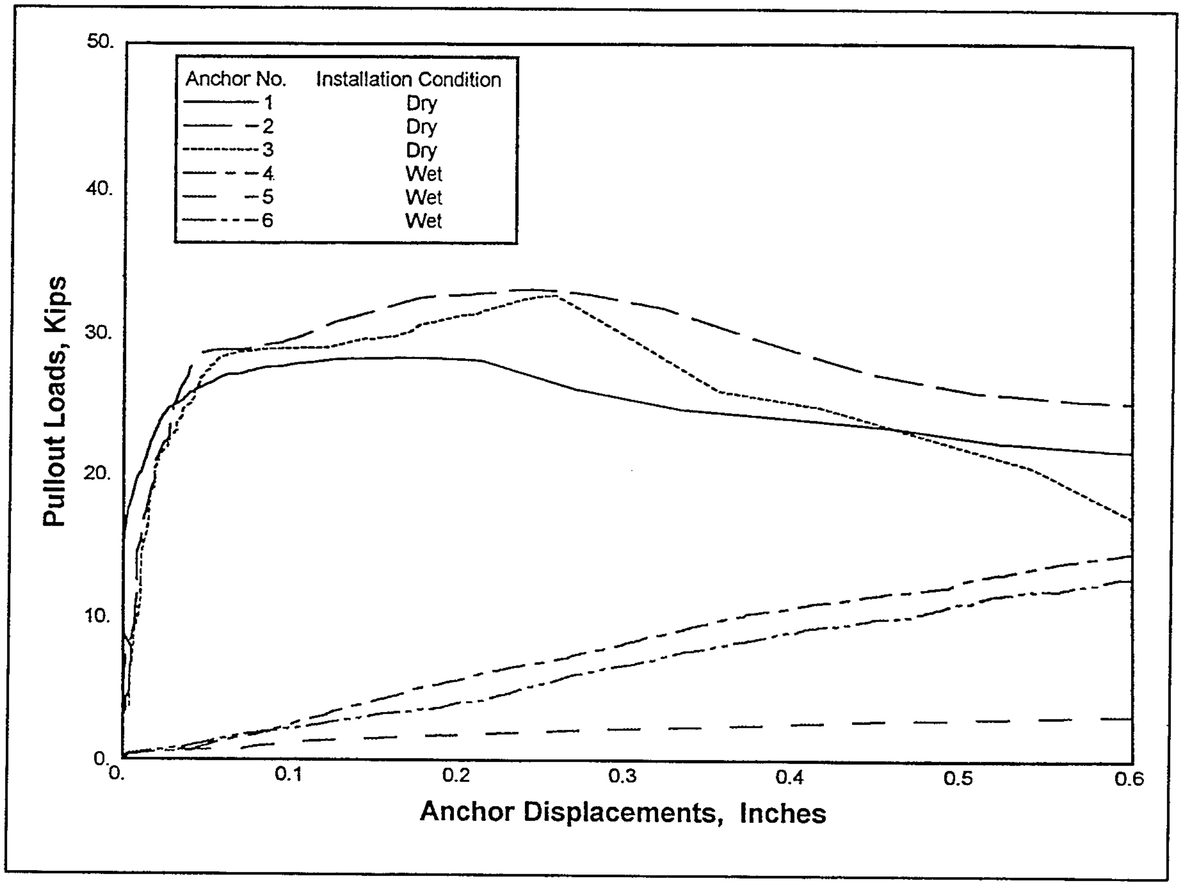


Figure 17. Results of pullout tests conducted at 1 day on anchors bonded with Adhesive B

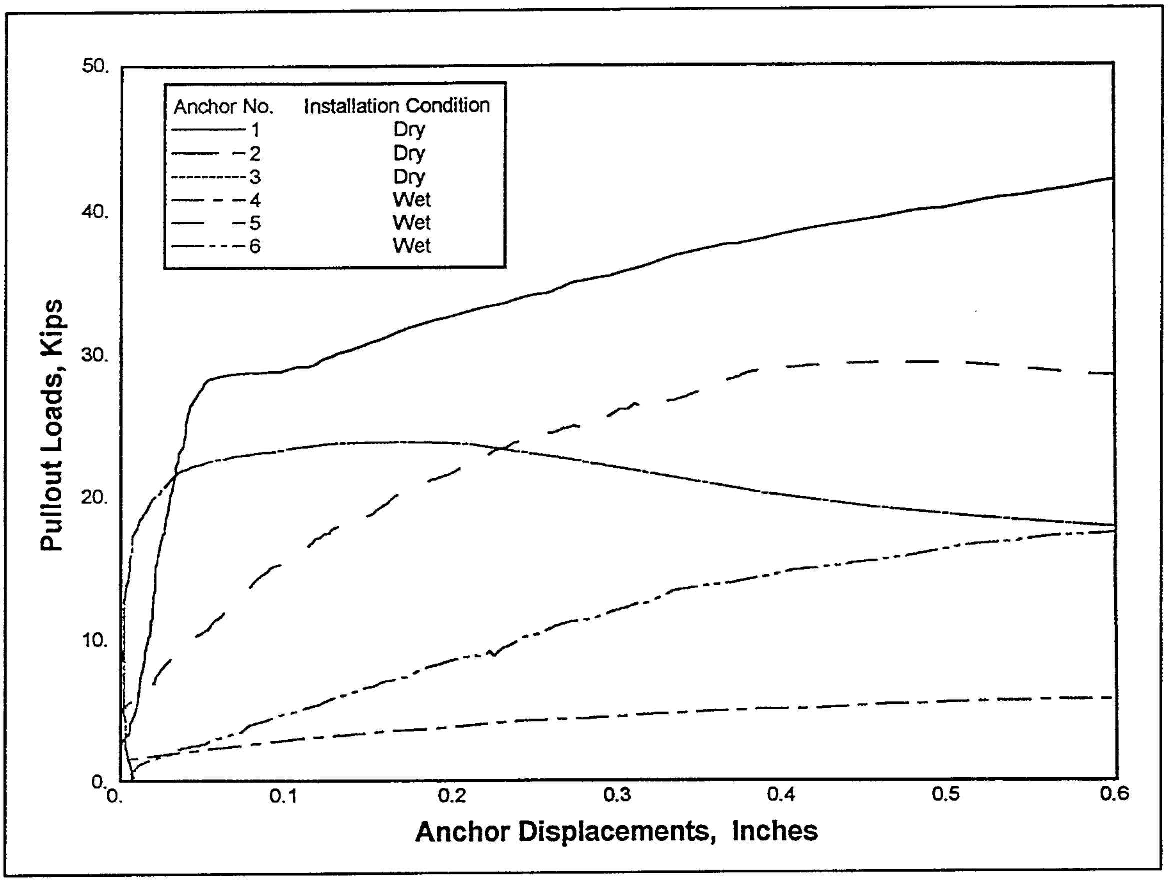


Figure 18. Results of pullout tests conducted at 3 days on anchors bonded with Adhesive B

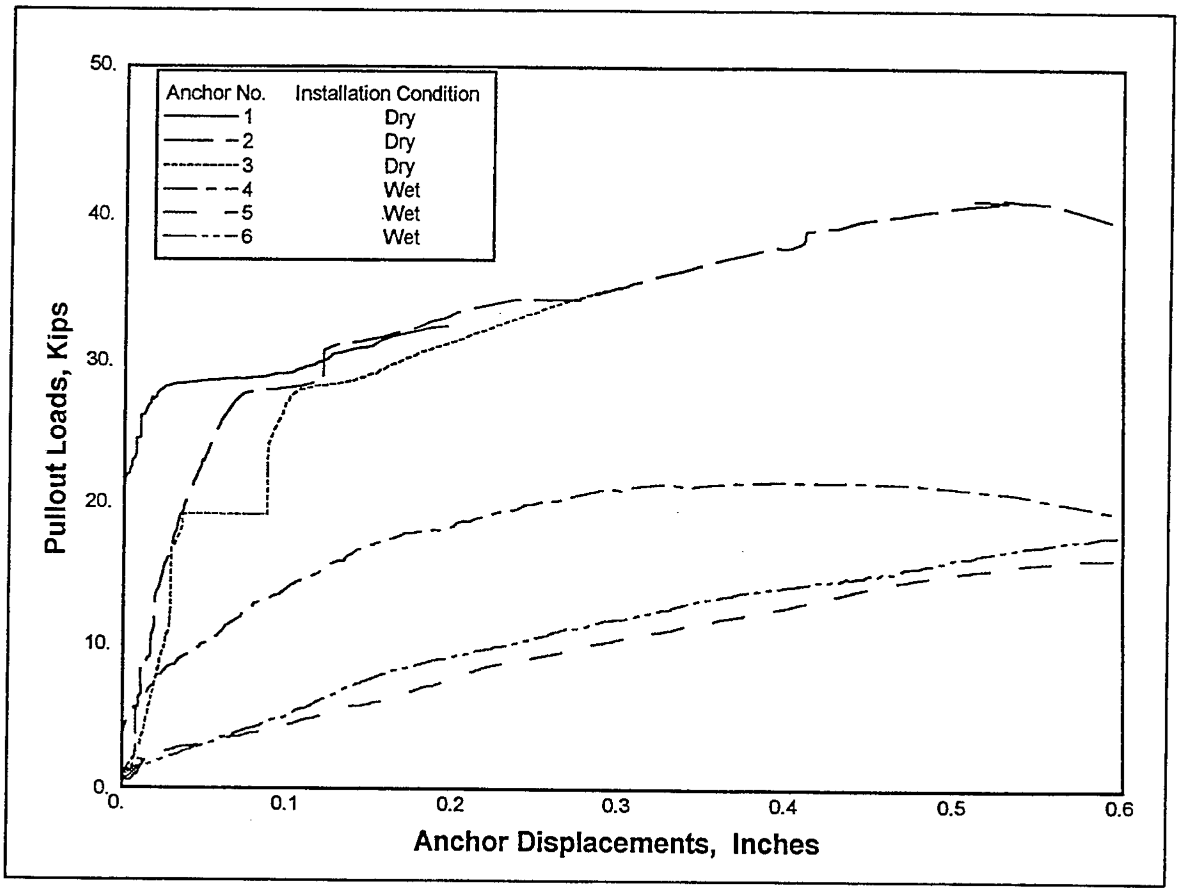


Figure 19. Results of pullout tests conducted at 7 days on anchors bonded with Adhesive B

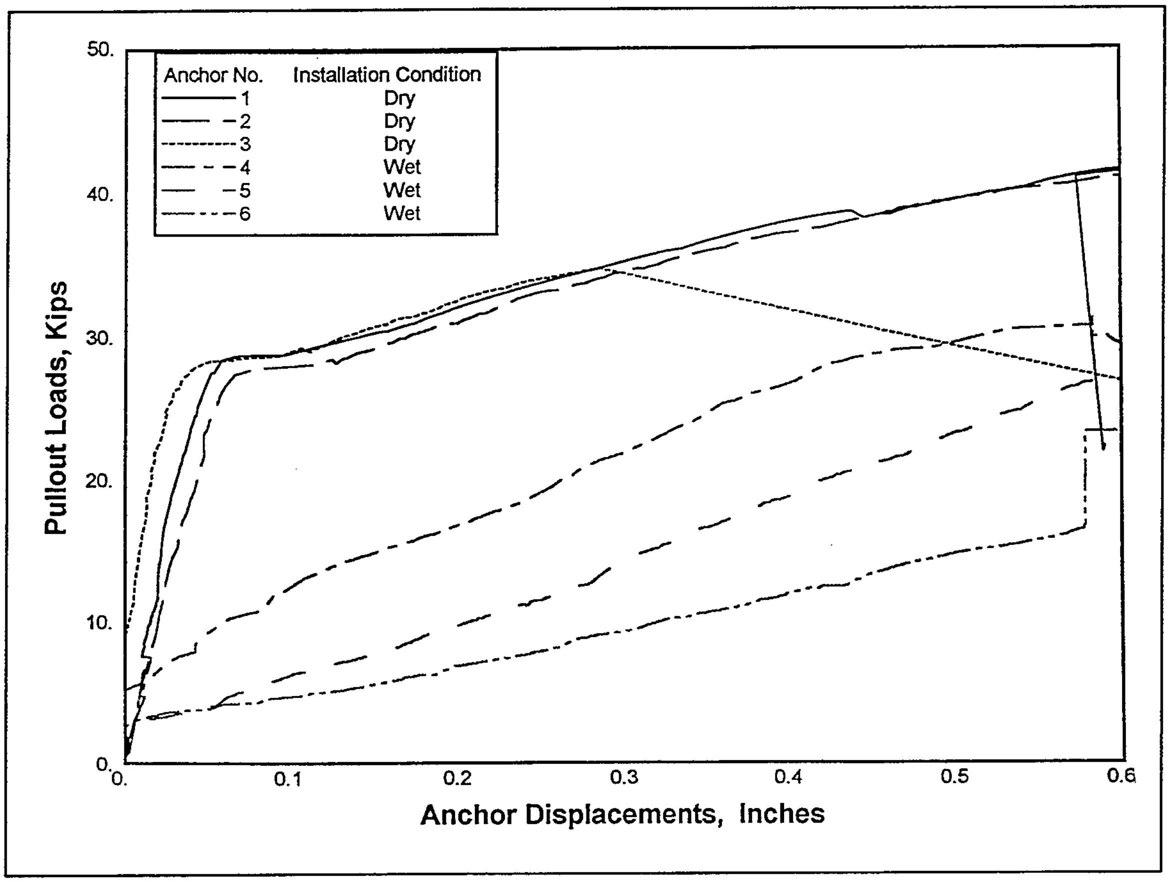


Figure 20. Results of pullout tests conducted at 28 days on anchors bonded with Adhesive B

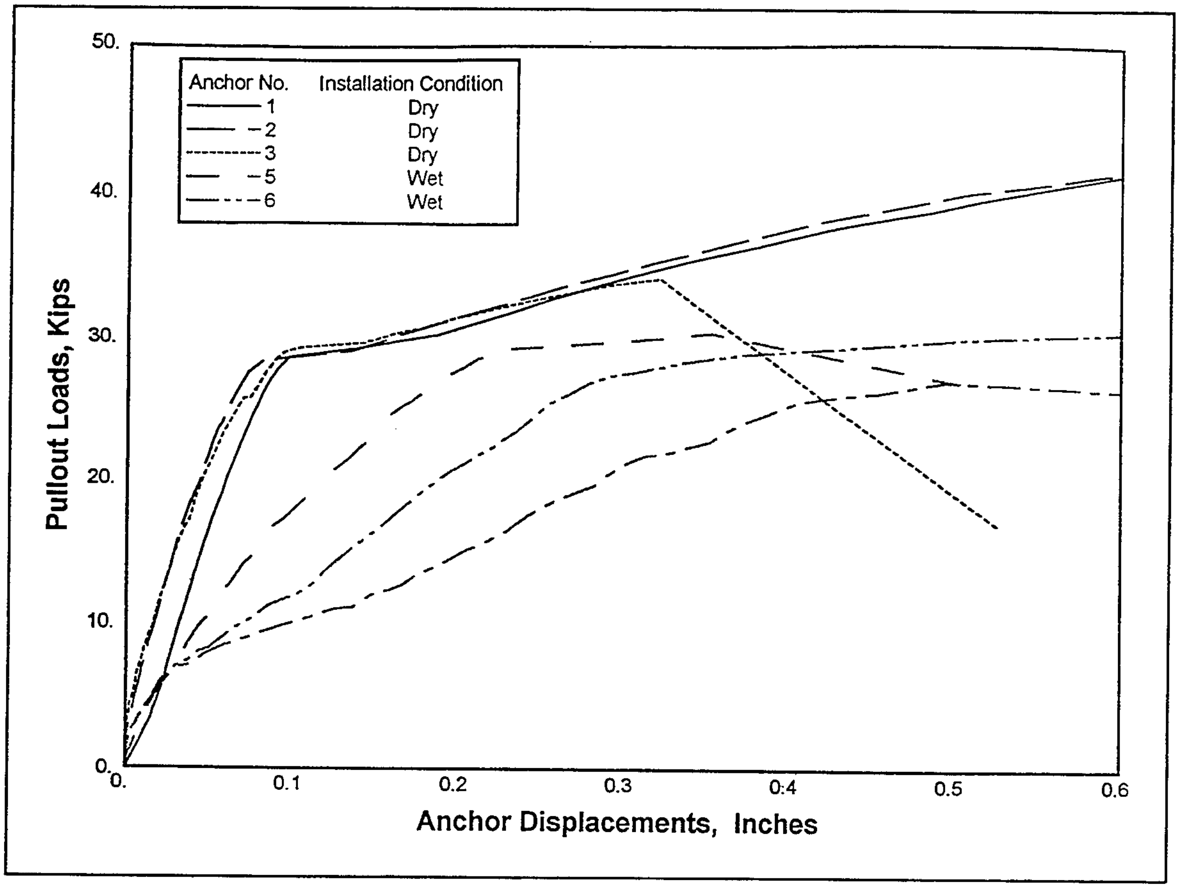


Figure 21. Results of pullout tests conducted at 1 year on anchors bonded with Adhesive B

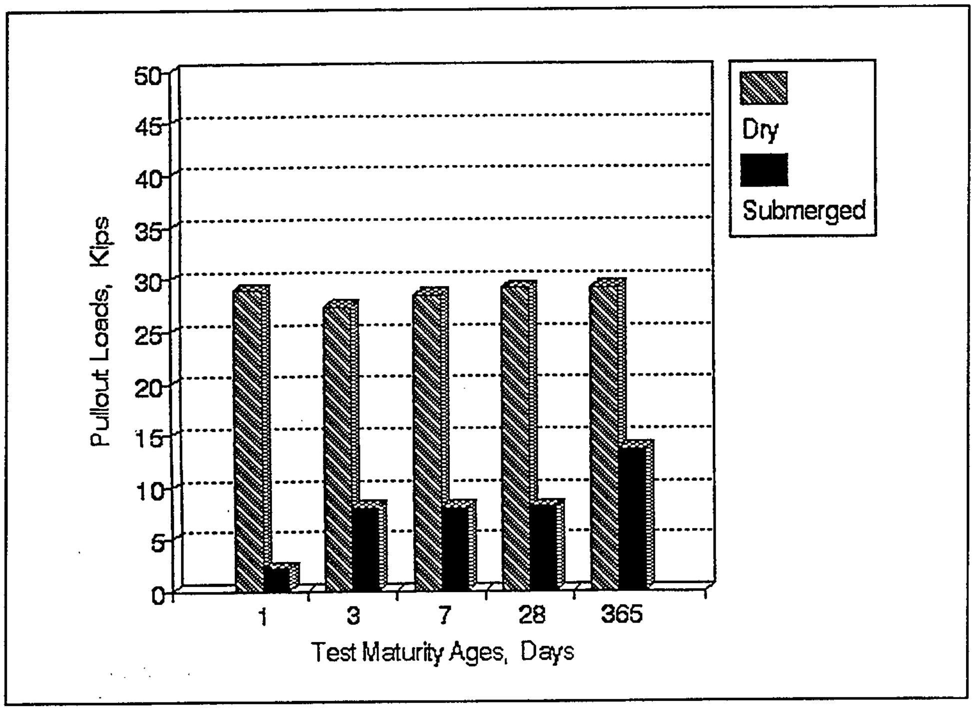


Figure 22. Average tensile capacity at 0.254-cm (0.1-in.) displacements of anchors installed with Adhesive B under dry and submerged conditions

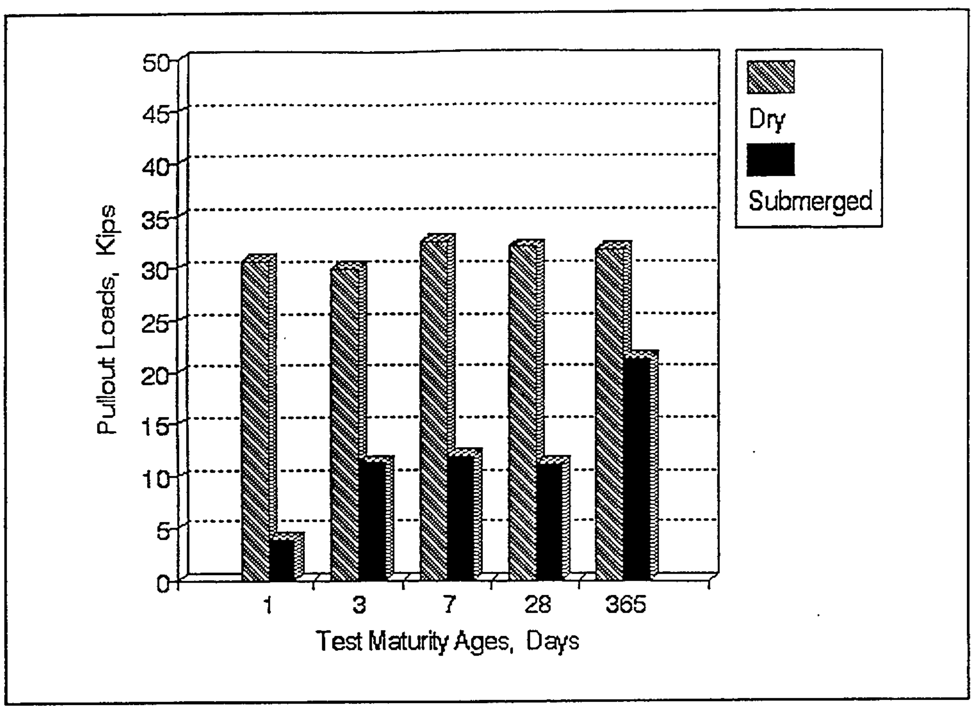


Figure 23. Average tensile capacity at 0.508-cm (0.2-in.) displacements of anchors installed with Adhesive B under dry and submerged conditions

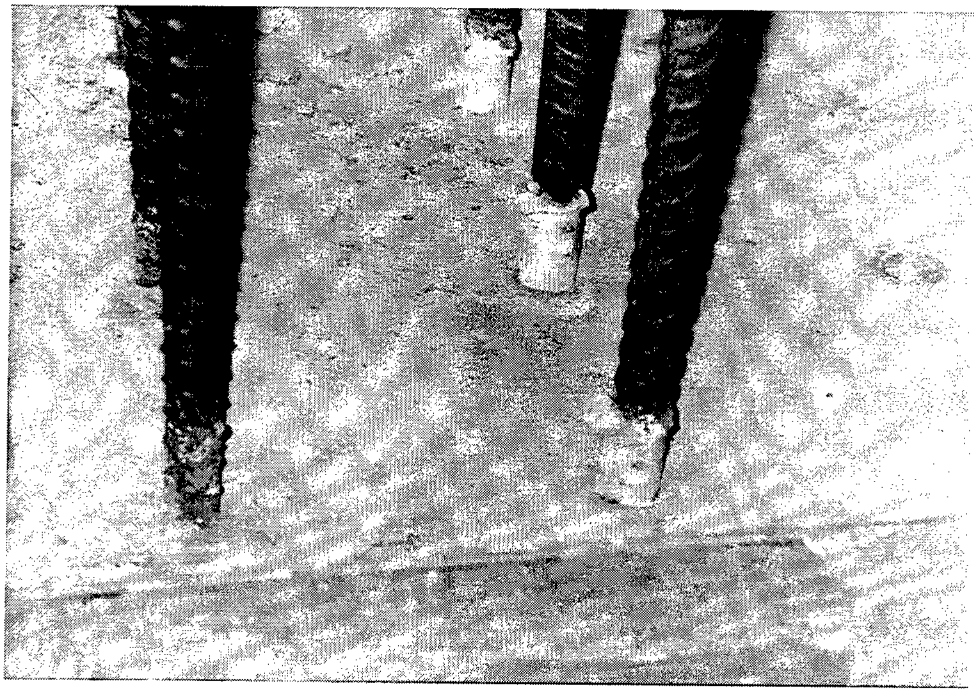


Figure 24. Typical failure for submerged anchors installed with Adhesives A and B

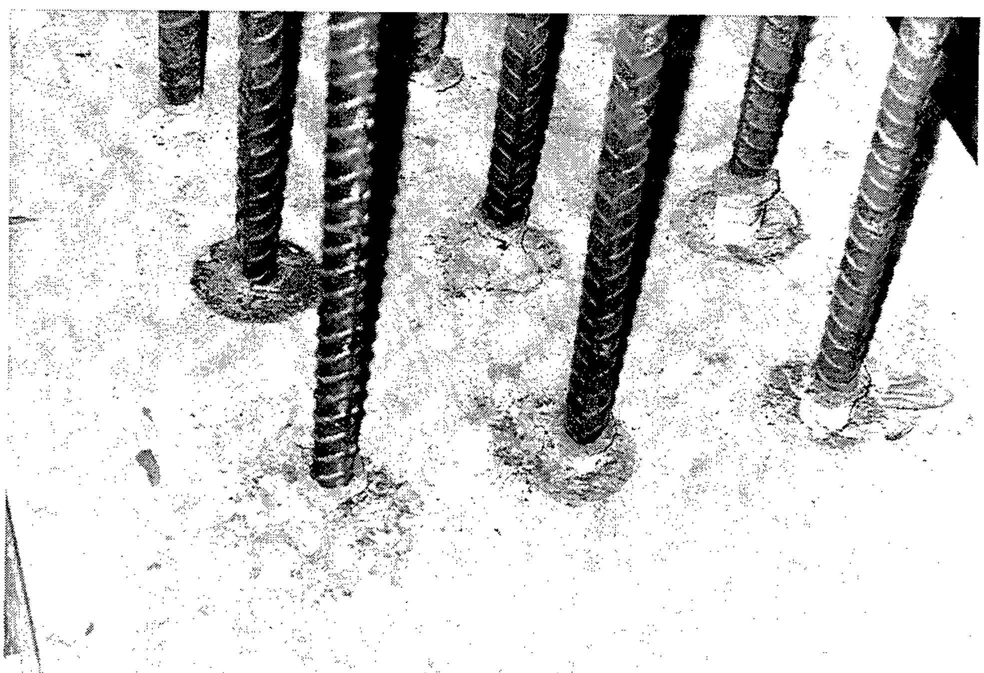


Figure 25. Typical material fracture normally occurring during anchor failure

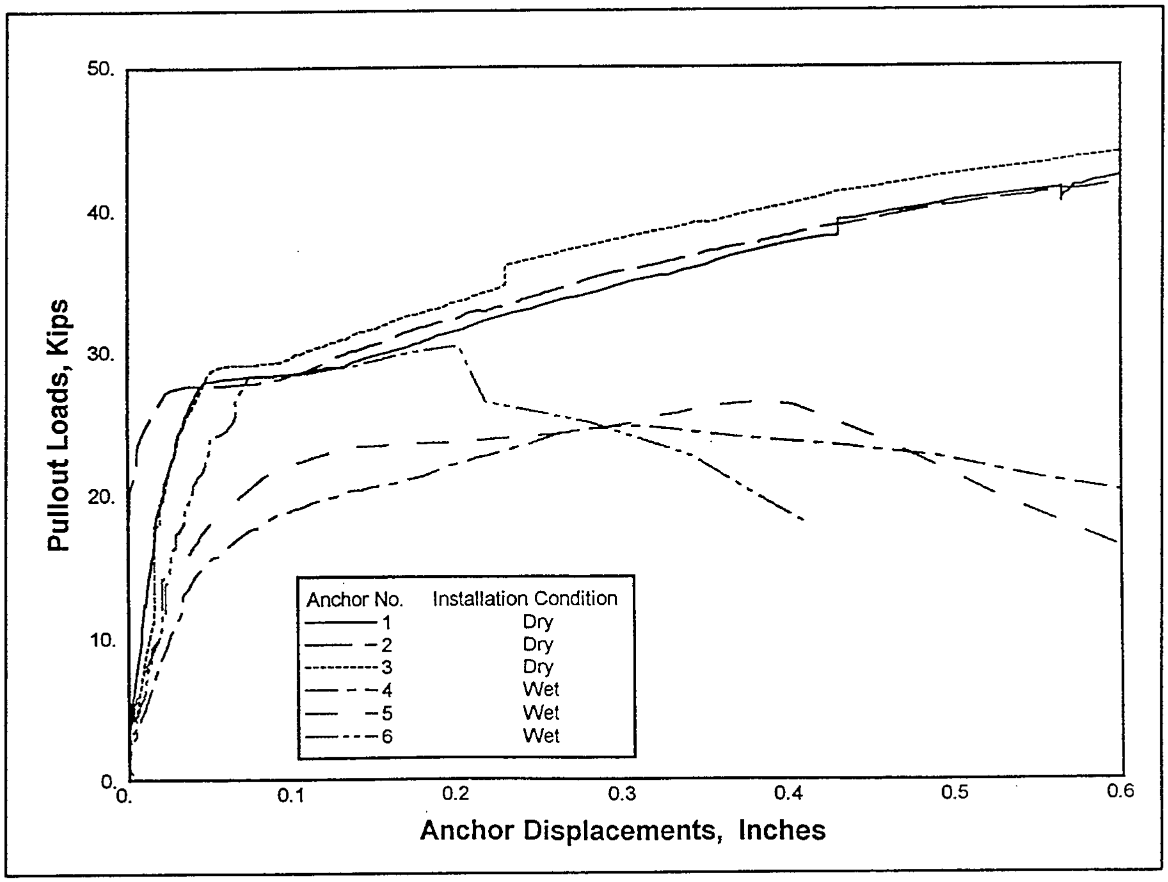


Figure 26. Results of pullout tests conducted at 1 day on anchors bonded with Adhesive C

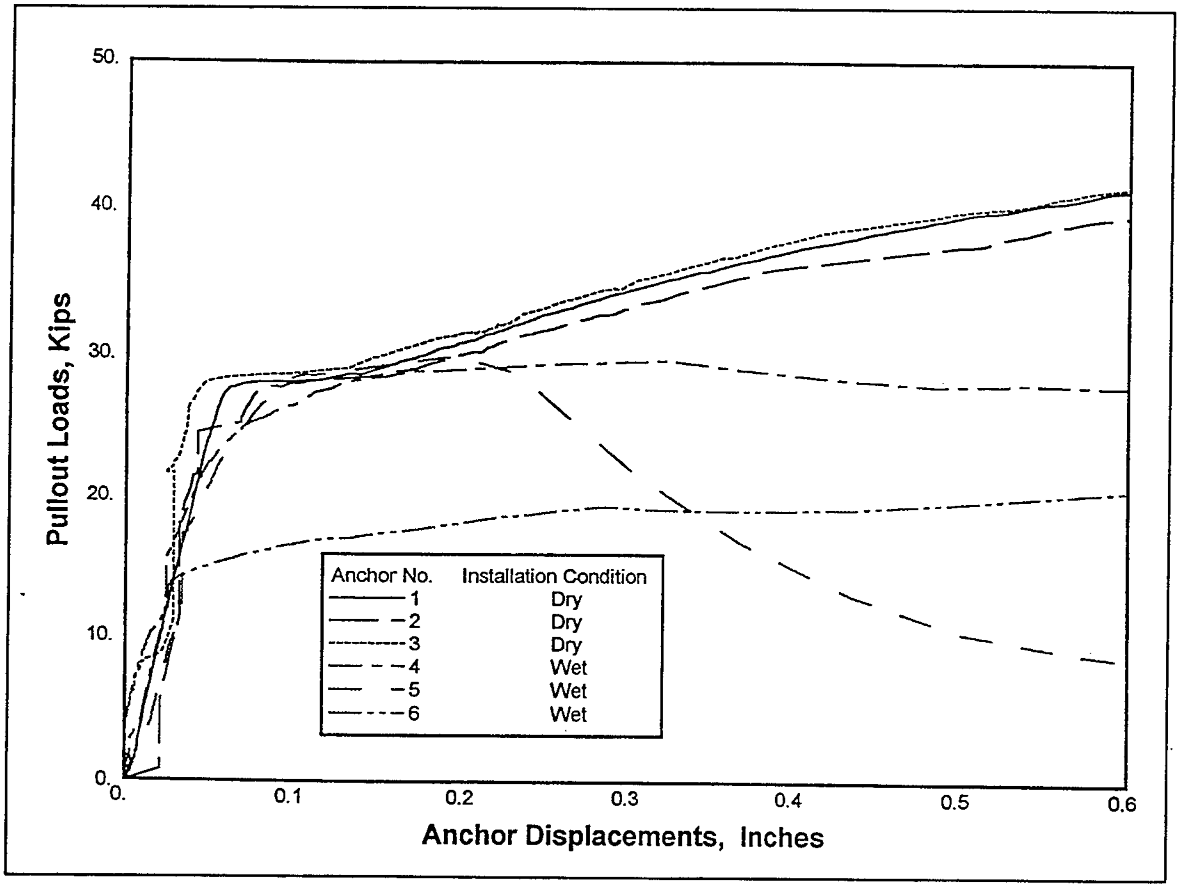


Figure 27. Results of pullout tests conducted at 3 days on anchors bonded with Adhesive C

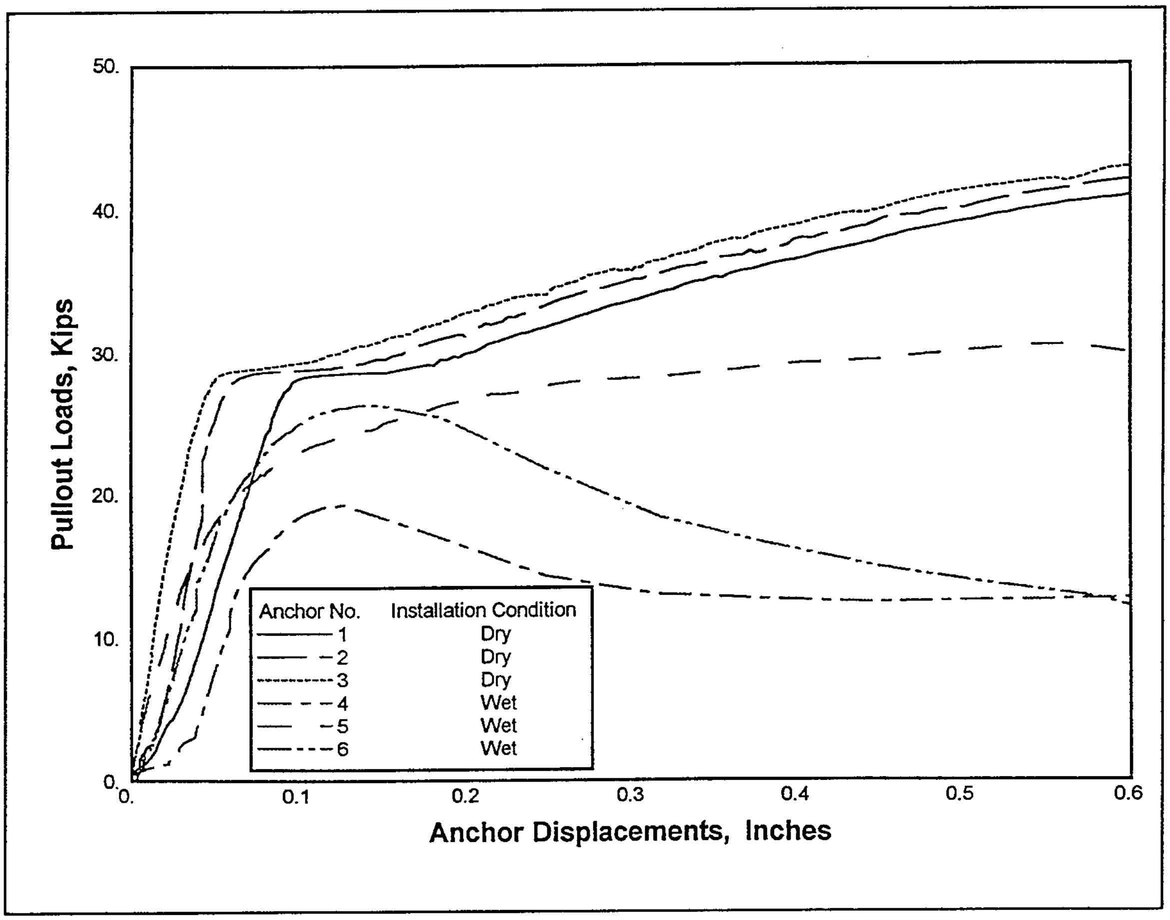


Figure 28. Results of pullout tests conducted at 7 days on anchors bonded with Adhesive C

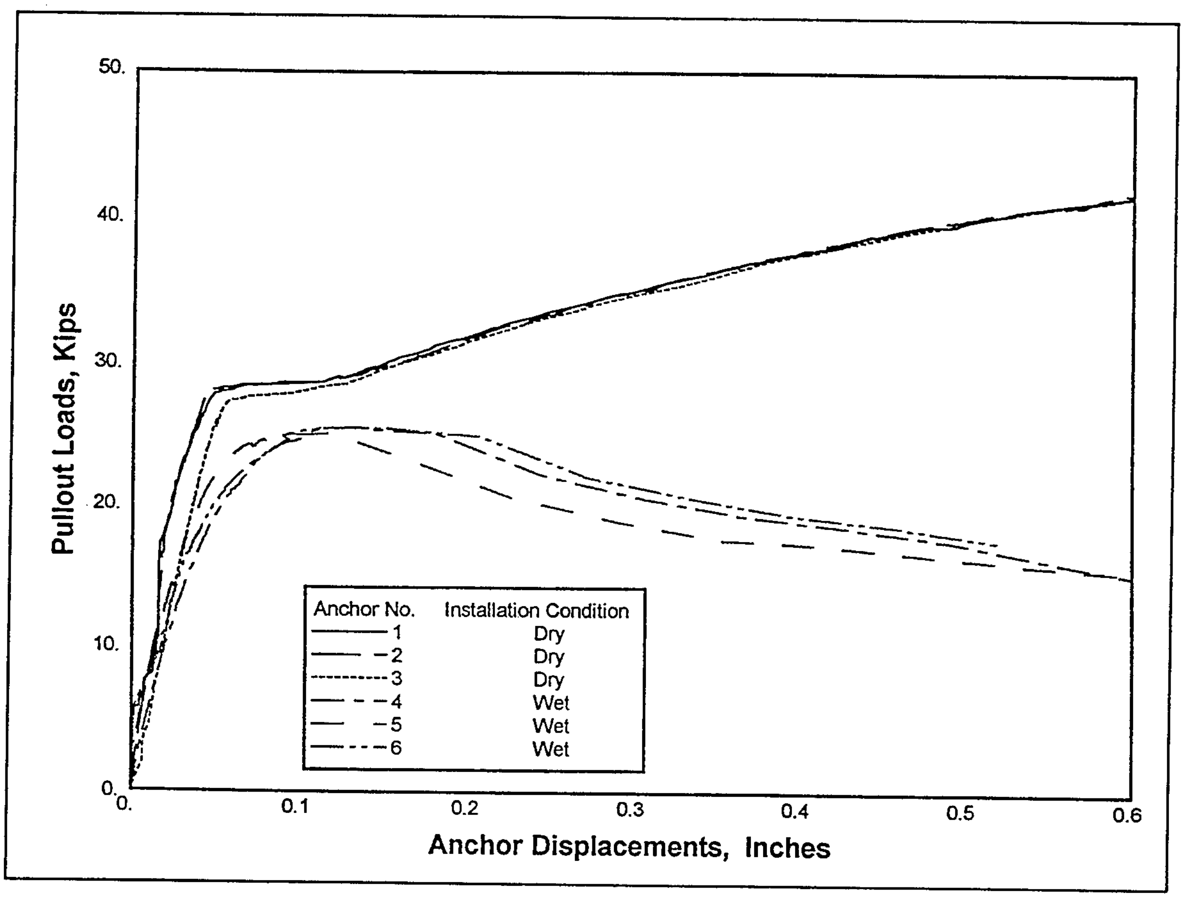


Figure 29. Results of pullout tests conducted at 28 days on anchors bonded with Adhesive C

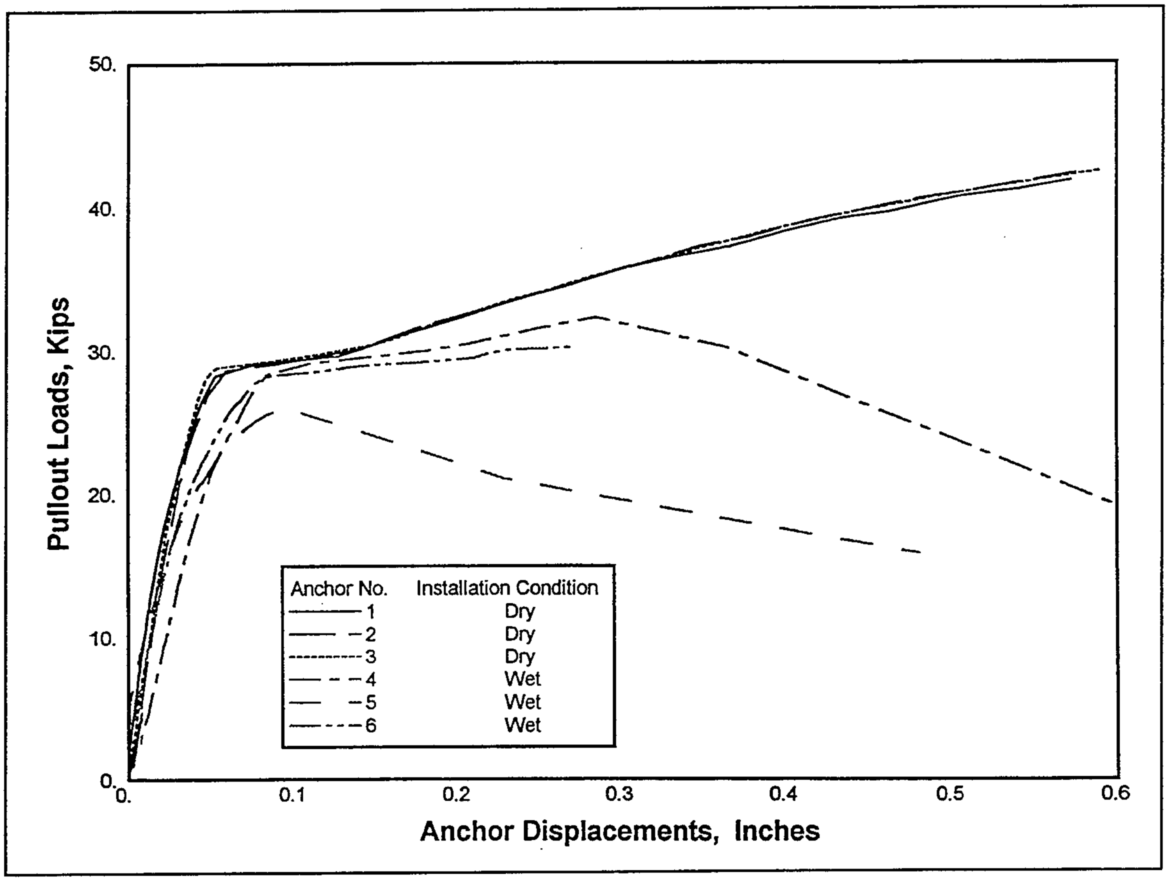


Figure 30. Results of pullout tests conducted at 1 year on anchors bonded with Adhesive C

submerged installations at 0.254- and 0.508-cm (0.1- and 0.2-in.) anchor displacements are shown in Figures 31 and 32, respectively.

Adhesive D (vinylester)

Adhesive D was used only for bonding dry installation of anchors. Maximum tensile capacities sustained by these averaged slightly lower than the ultimate strength of the anchors. Significantly lower tensile capacities given for long-term (1-year) tests on these anchors are attributed to edge failures within the concrete block. Pullout loads versus displacements are plotted for these anchors in Figures 33 through 37. Anchor performances at 0.254- and 0.508-cm (0.1- and 0.2-in.) displacements consistently average sustained tensile capacities greater than the anchors' yield strength.

Adhesive E (cementitious)

Pullout test results for applications of Adhesive E in submerged anchors installations are shown in Figures 38 through 42. With the exception of long-term (1-year) tests, performances by these anchors were consistent throughout all evaluations. During storage of the concrete block containing the 1-year anchor installations, inadvertent leakage of ponded water exposed the anchors to periods of dry conditions (several days). As a result, such a condition is believed to have disrupted the hydration process of the cementitious adhesive, thus causing reductions in the tensile capacities as indicated. The average maximum tensile capacities were within the range of the anchors' ultimate strength (except for about a 20-percent reduction in 3- and 7-day tests). Average tensile capacities at 0.254- and 0.508-cm (0.1- and 0.2-in.) displacements were equal to or greater than the yield strength of the anchors.

Creep Tests

Results of creep tests for dry and submerged anchor installations are summarized in Appendix B, Tables B1 through B7, for each adhesive product. Results are given for 6 months of sustained loading of the anchors at 60 percent of the anchors' yield strength. Figures 43 and 44 represent graphic plots of anchor performances in creep tests for dry and submerged anchor installations, respectively. The basis for comparisons of anchor performances is considered by anchor slippage which is depicted by plots of measured displacements versus time.

After 6 months of sustained loading, anchor performances in creep tests followed a similar trend as in pullout tests. For Adhesives A, dry installations exhibited low average slippage of 0.001 cm (0.0005 in.) while submerged installations exhibited 76 times higher average slippage of 0.097 cm (0.0380 in.) (average of two anchor specimens). Average slippage exhibited by dry

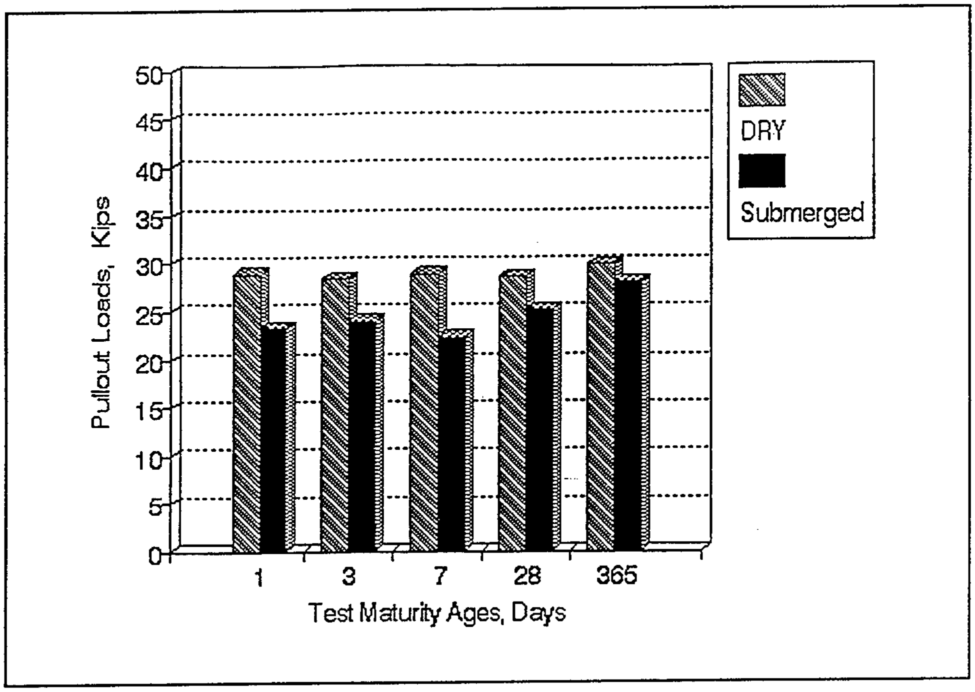


Figure 31. Average tensile capacity at 0.254-cm (0.1-in.) displacements of anchors installed with Adhesive C under dry and submerged conditions

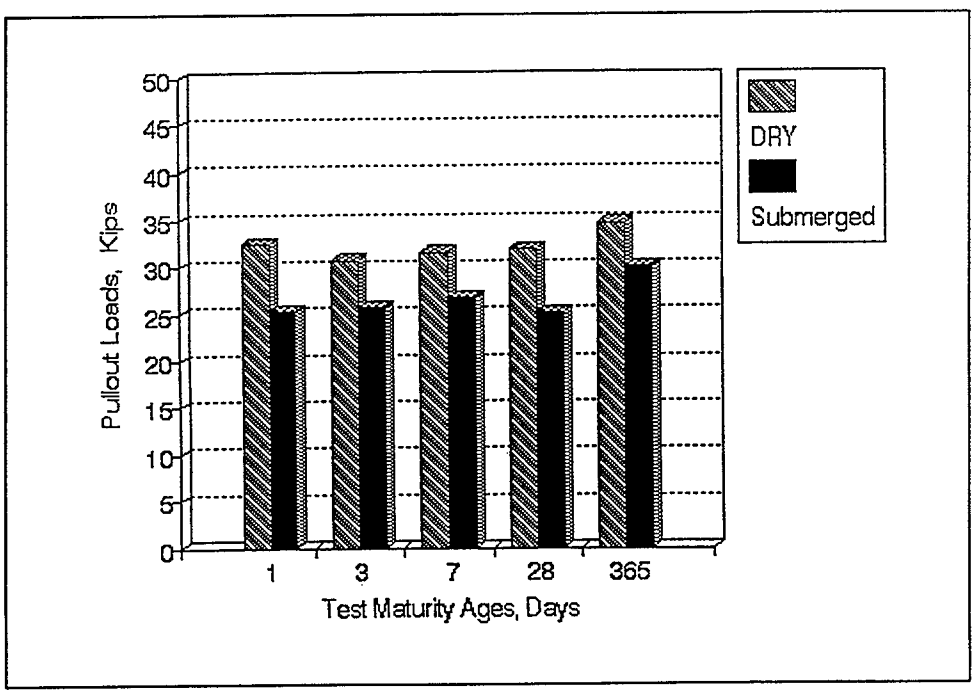


Figure 32. Average tensile capacity at 0.508-cm (0.2-in.) displacements of anchors installed with Adhesive C under dry and submerged conditions

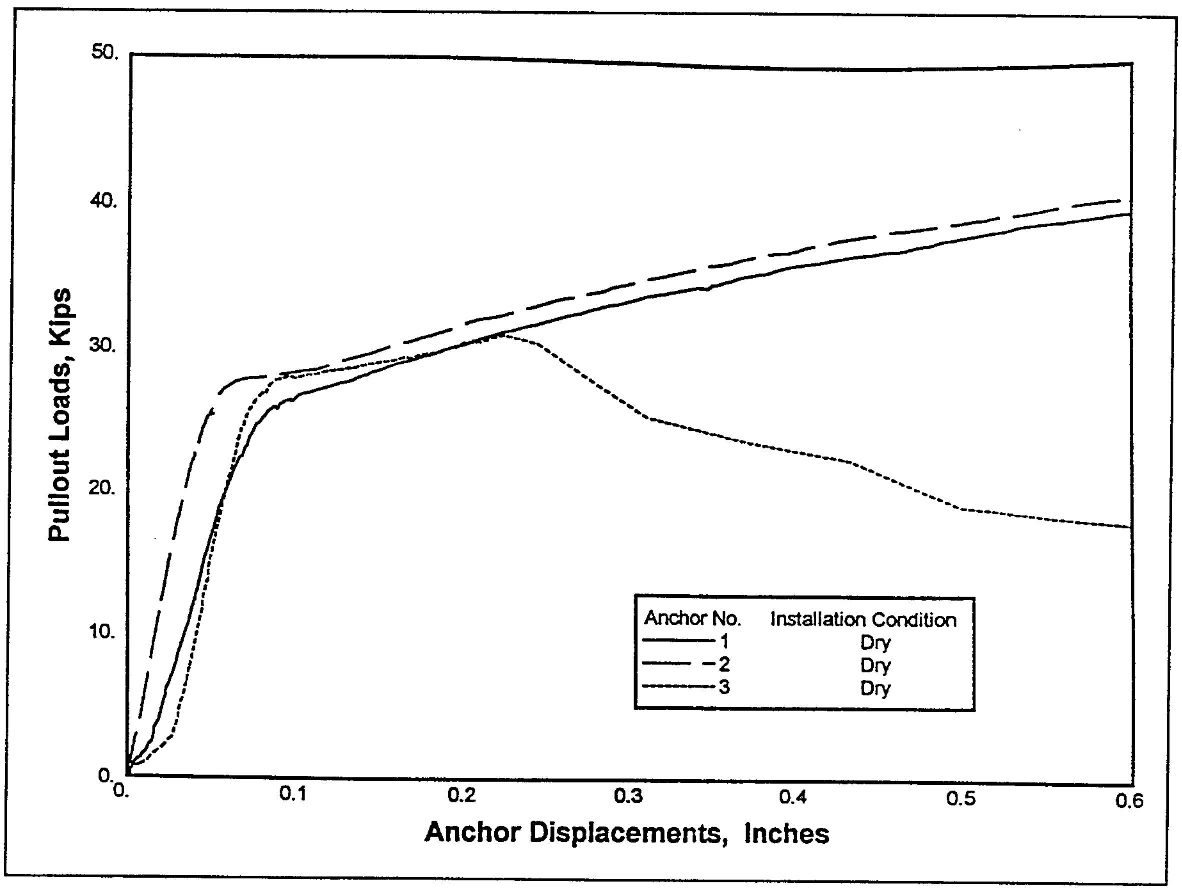


Figure 33. Results of pullout tests conducted at 1 day on anchors bonded with Adhesive D

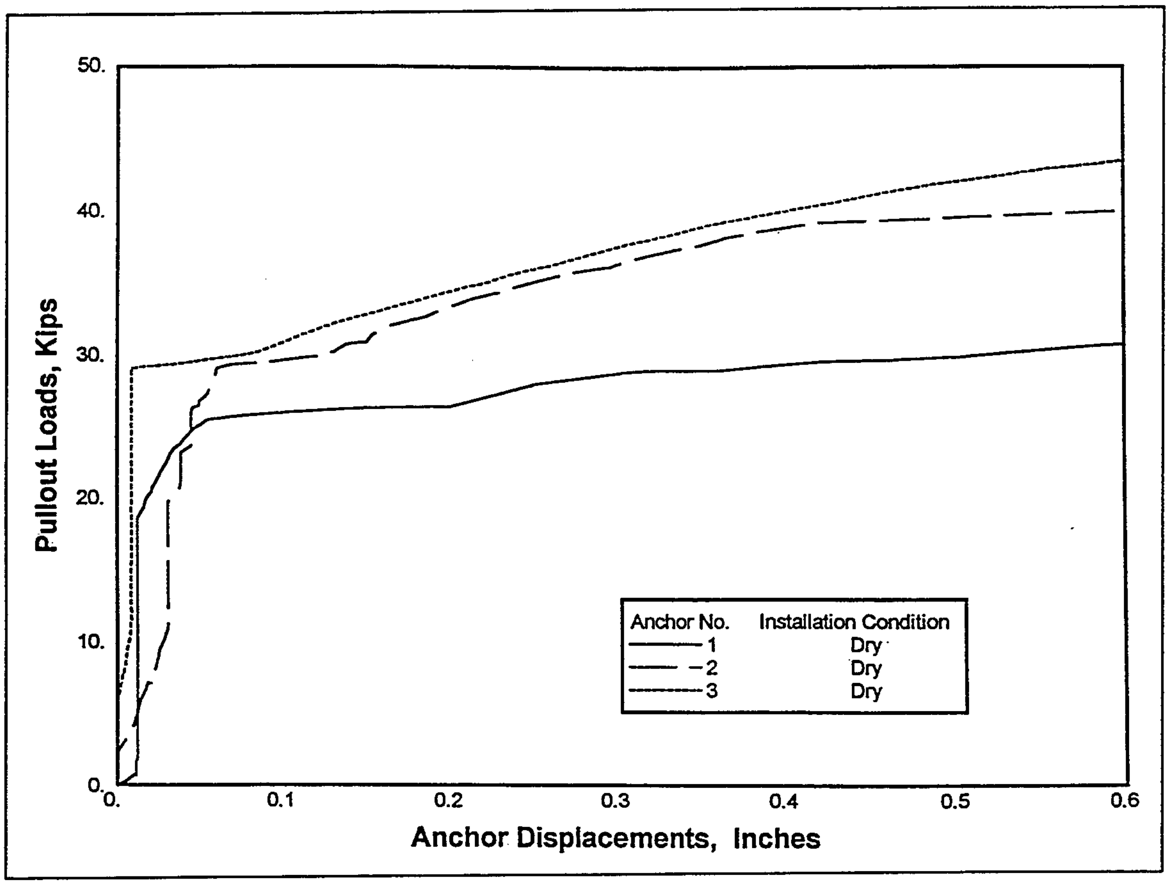


Figure 34. Results of pullout tests conducted at 3 days on anchors bonded with Adhesive D

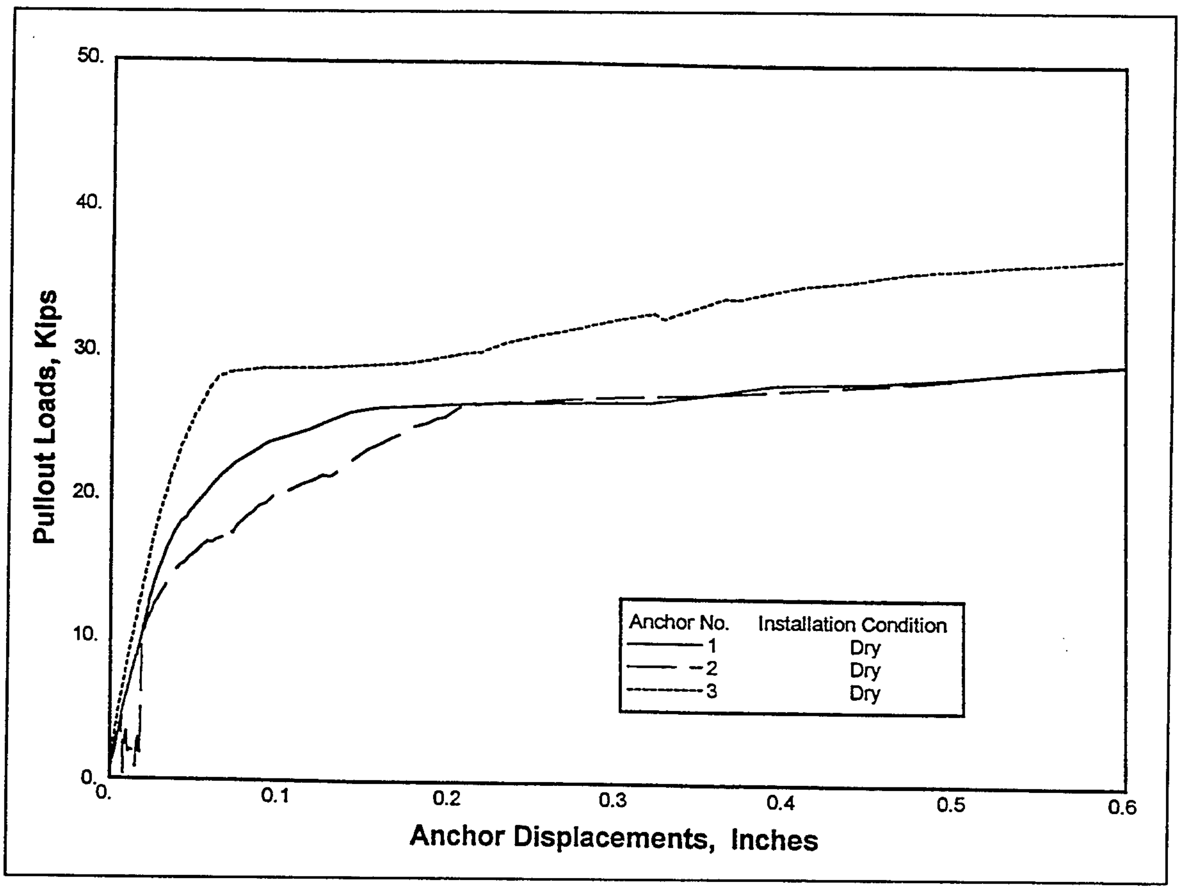


Figure 35. Results of pullout tests conducted at 7 days on anchors bonded with Adhesive D

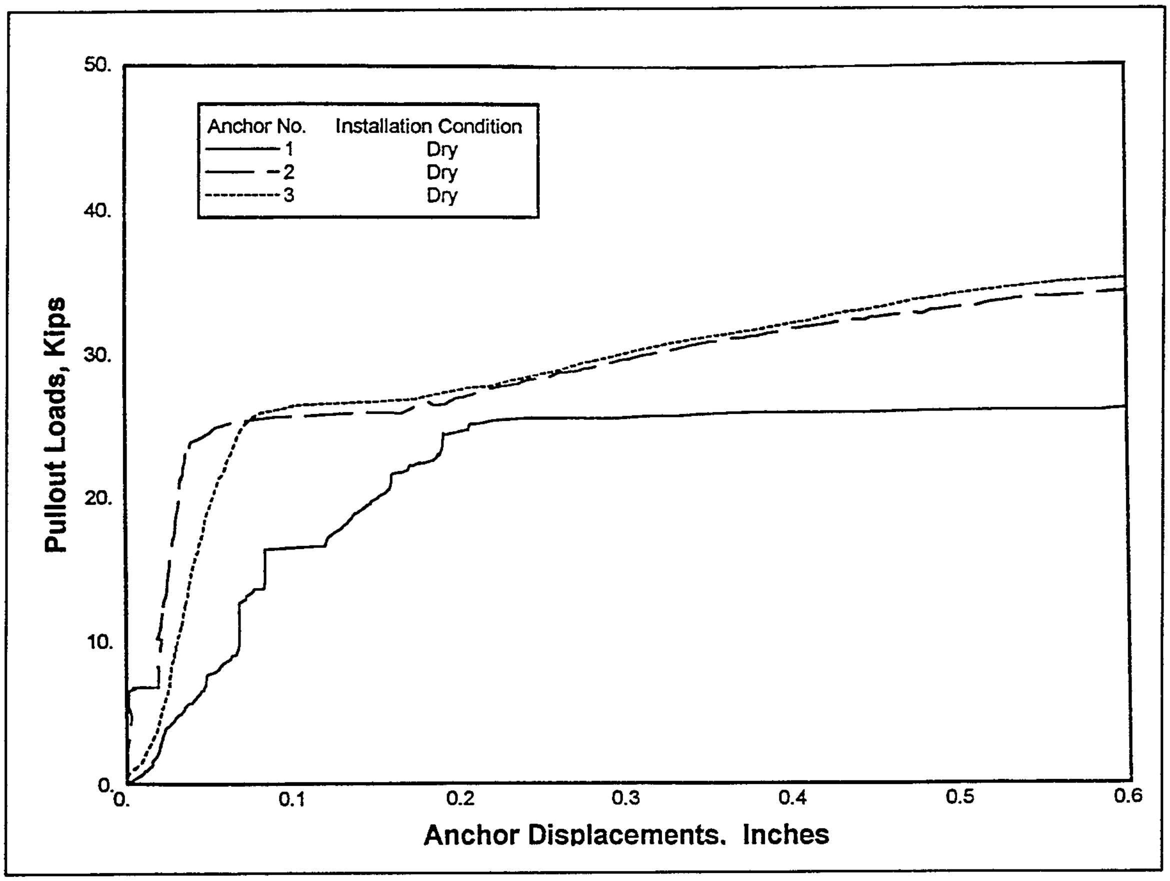


Figure 36. Results of pullout tests conducted at 28 days on anchors bonded with Adhesive D

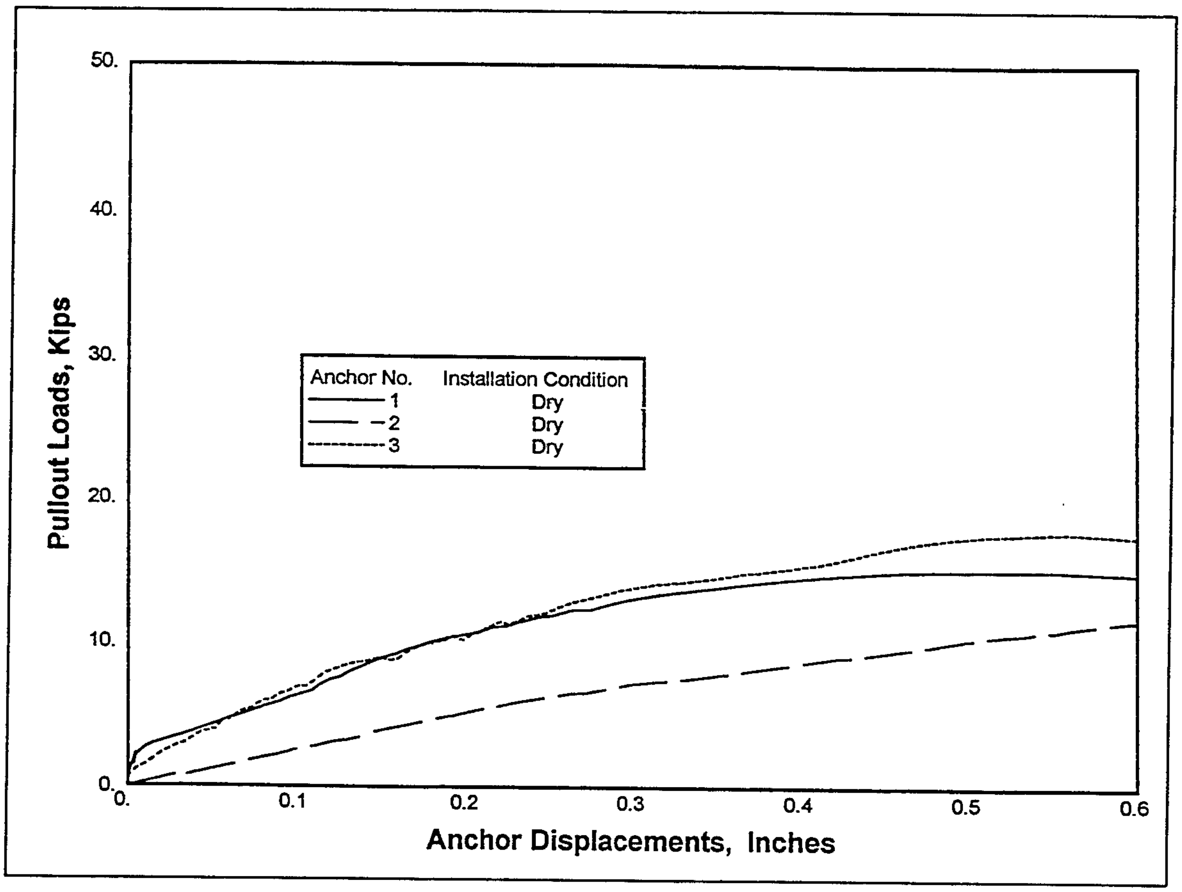


Figure 37. Results of pullout tests conducted at 1 year on anchors bonded with Adhesive D

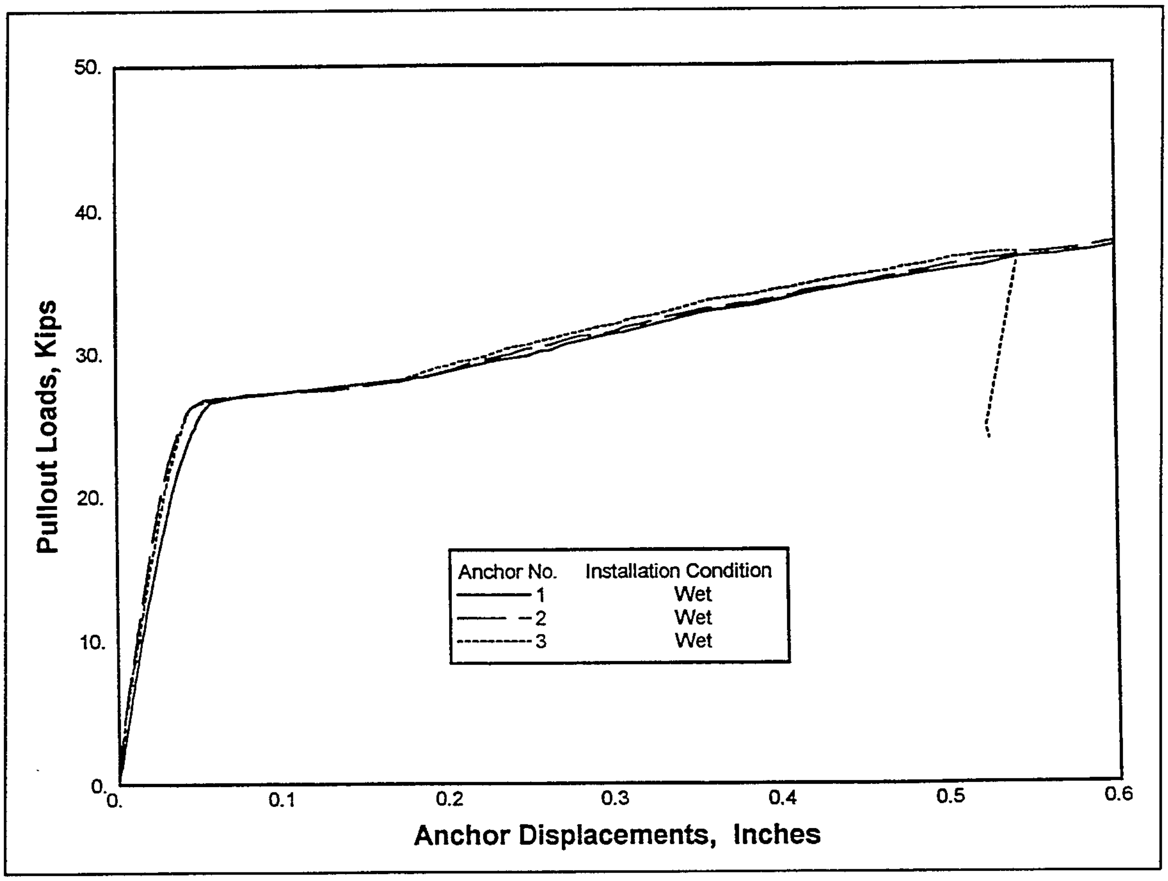


Figure 38. Results of pullout tests conducted at 1 day on anchors bonded with Adhesive E

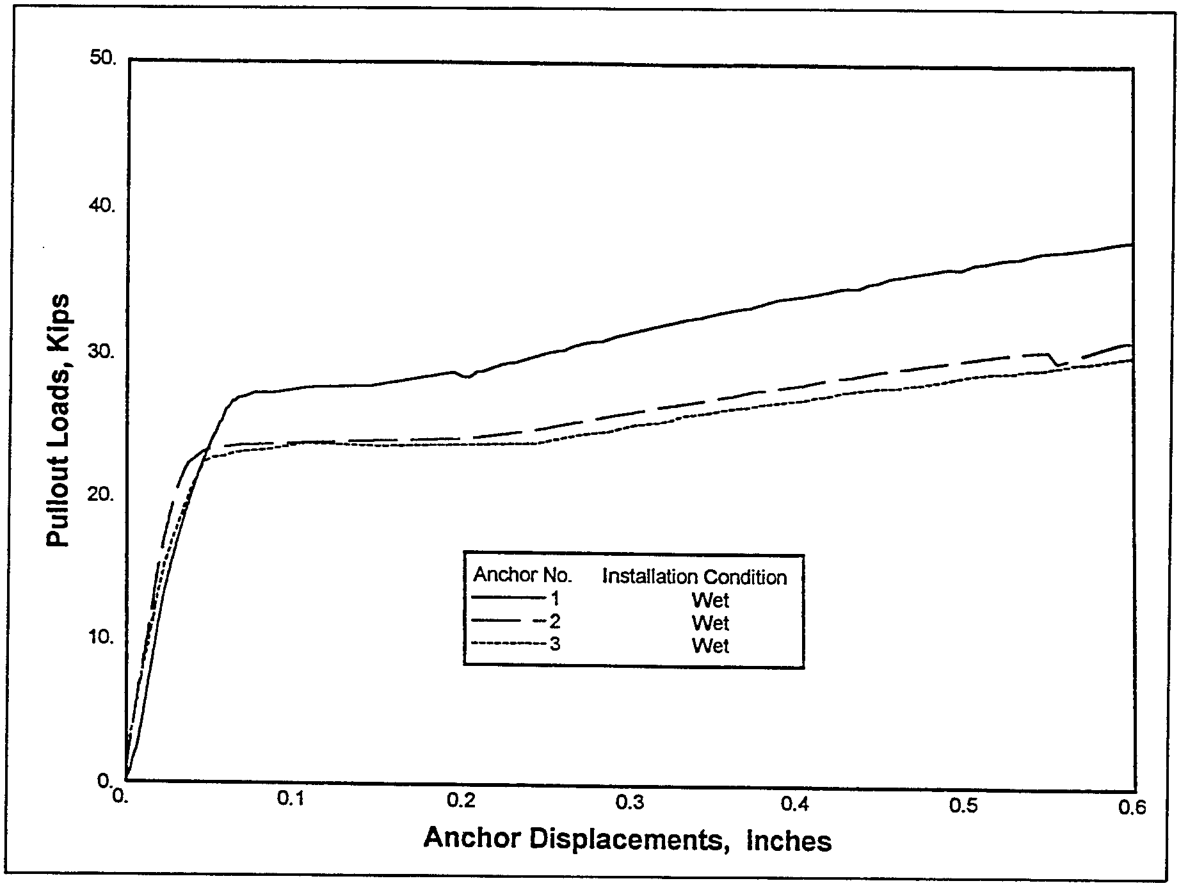


Figure 39. Results of pullout tests conducted at 3 days on anchors bonded with Adhesive E

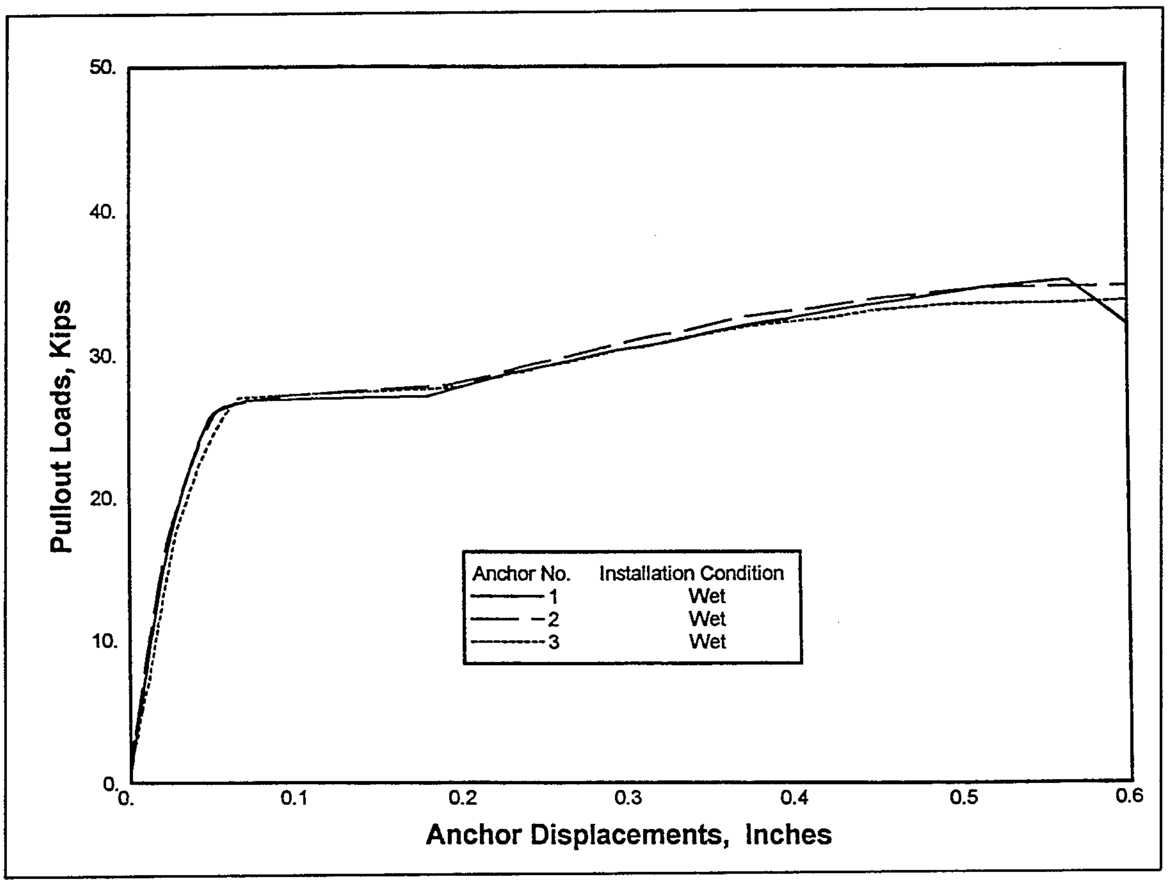


Figure 40. Results of pullout tests conducted at 7 days on anchors bonded with Adhesive E

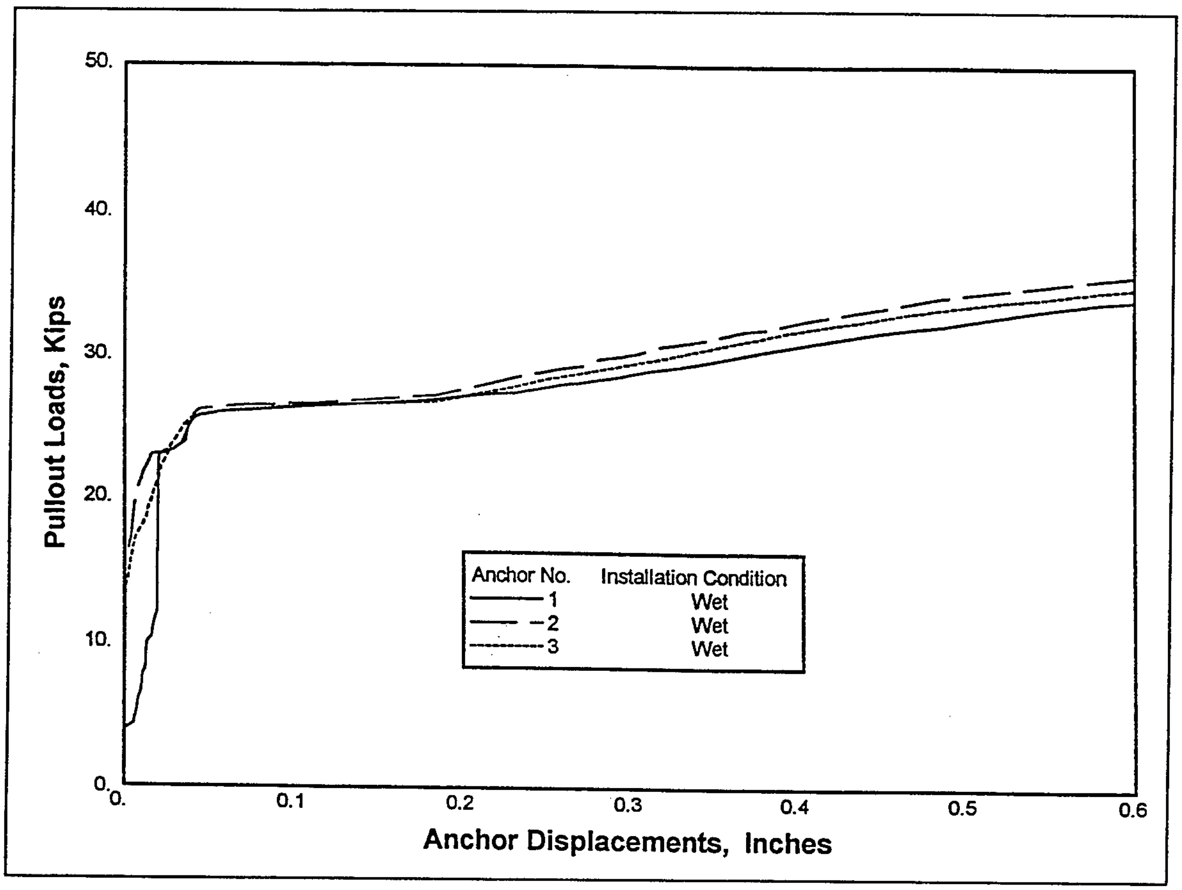


Figure 41. Results of pullout tests conducted at 28 days on anchors bonded with Adhesive E

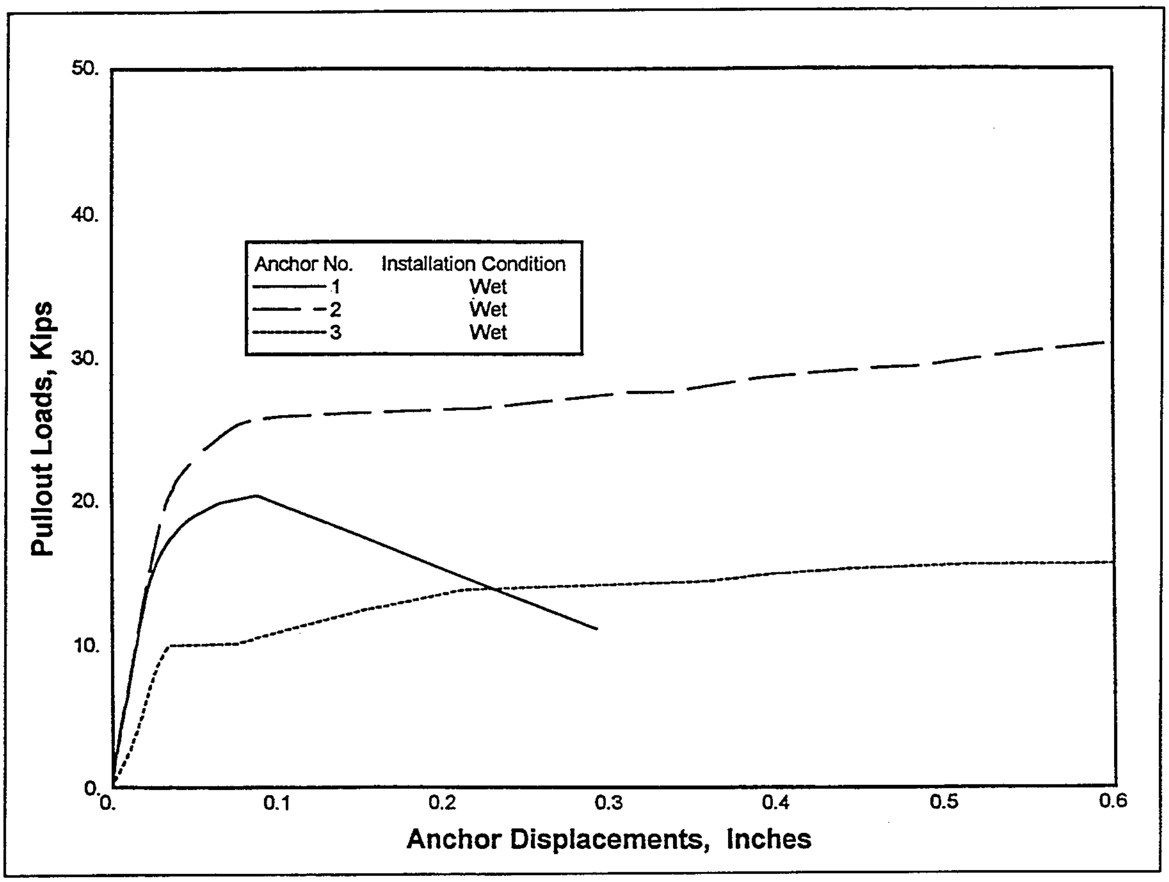


Figure 42. Results of pullout tests conducted at 1 year on anchors bonded with Adhesive E

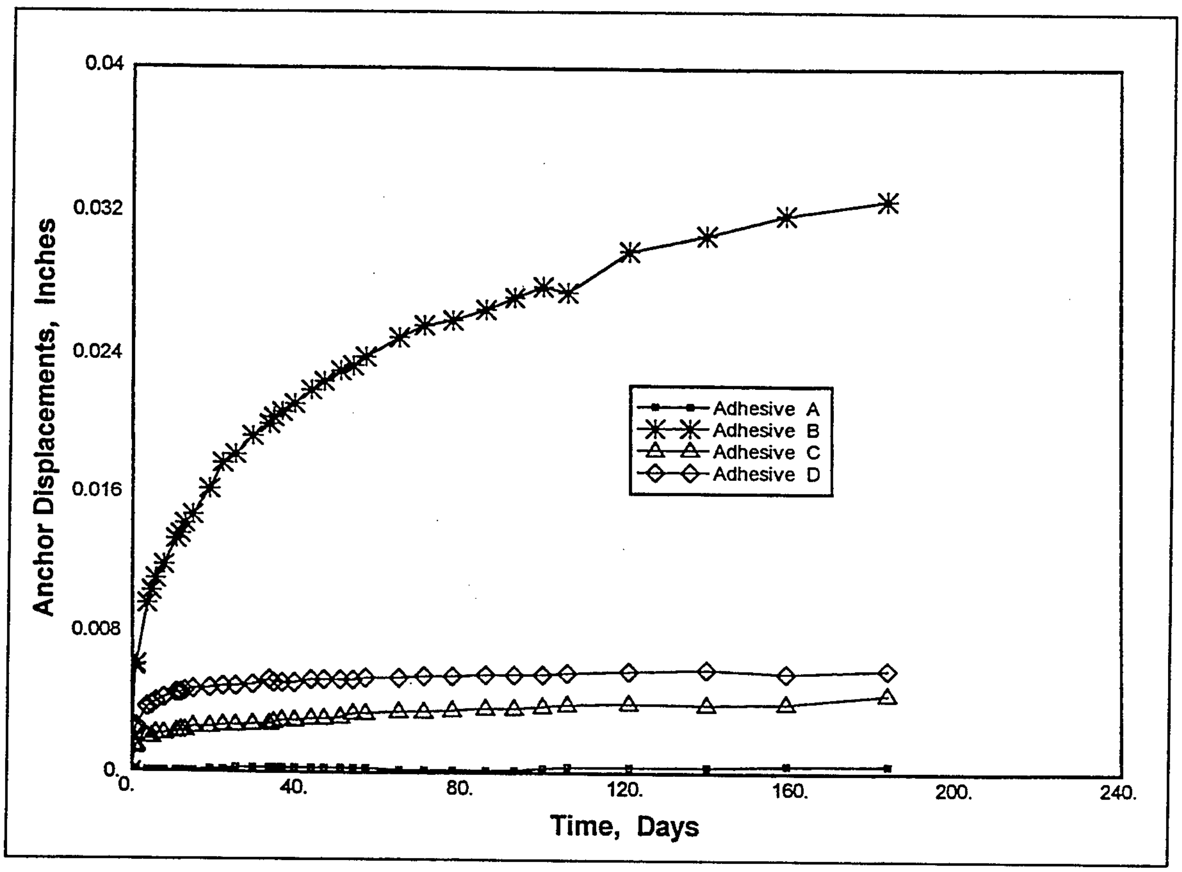


Figure 43. Results of creep tests for dry anchor installations

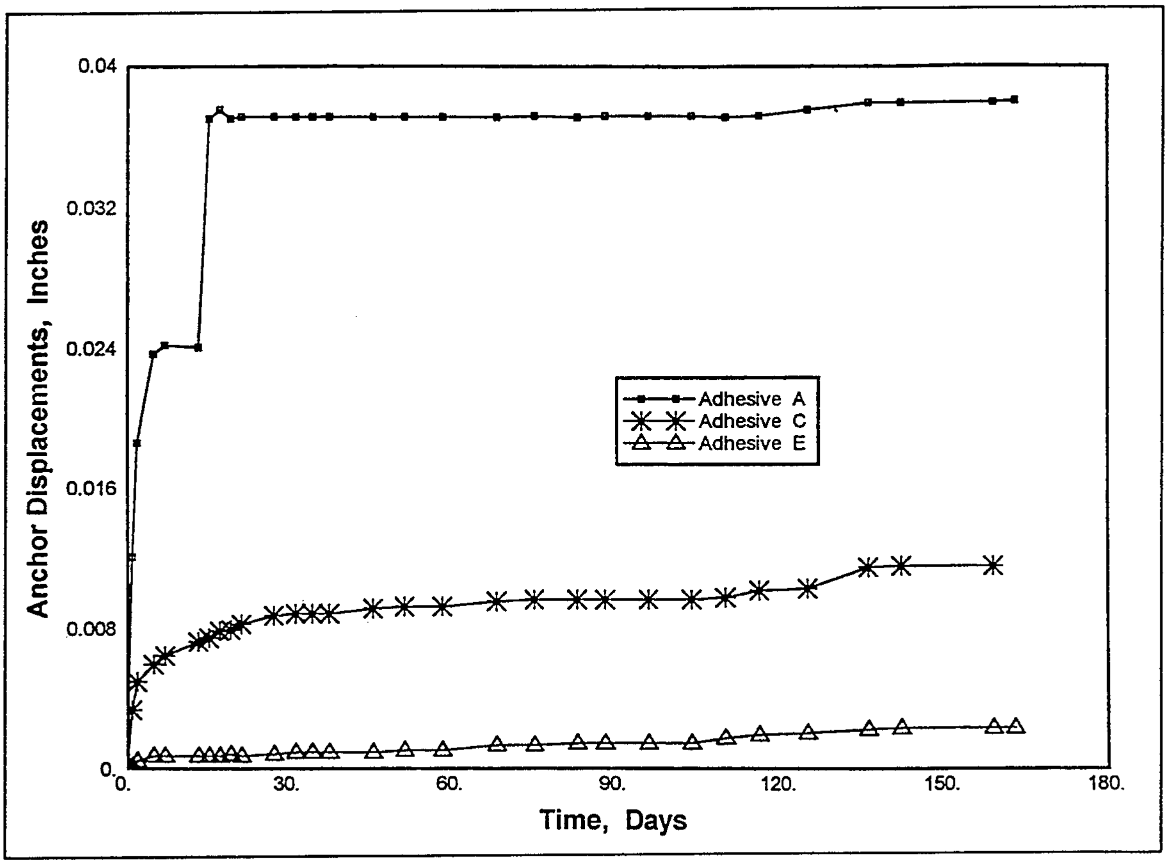


Figure 44. Results of creep tests for submerged anchor installations

installations with Adhesive B was 0.083 cm (0.0327 in.), while submerged installations failed during application of creep loading.

For Adhesive C, average slippage for dry and submerged installations were 0.011 and 0.029 cm (0.0045 and 0.0116 in.), respectively. Slippage for submerged installations were approximately two and one-half times higher than for dry installations. Both Adhesive D (dry installations) and Adhesive E (submerged installations) had low average slippage of 0.015 and 0.006 cm (0.0059 and 0.0024 in.), respectively.

4 Conclusions and Recommendations

Conclusions

In general, performances by the adhesives in pullout tests essentially followed a similar pattern as shown in previous studies.[1] Satisfactory results were obtained for installation of anchors under dry conditions for applications using each adhesive product. However, obvious reductions in tensile loading capacities were evident for anchor installations under submerged conditions. The best results achieved for anchor installations under submerged conditions were provided by Adhesive C and Adhesive E, respectively. Apparently, water remaining in the holes following insertion of Adhesive A and Adhesive B significantly affected the capabilities of these adhesives to sufficiently bond anchor installations under submerged conditions. This was indicated by the mode of failure in pullout tests in which there was no evidence of physical bonding at the interface of the adhesives and the inner walls of the drilled holes.

Results for performances by the adhesives (creep tests for dry anchor installations) indicated that with the exception of Adhesive B, each anchor provided satisfactory resistance to anchor slippage. Similar to patterns established in pullout test performances, significant reductions in performances by the adhesives were also seen in creep tests conducted for submerged anchor installations. Likewise, Adhesive C and Adhesive E again were the two adhesives that showed acceptable performances for submerged applications. By comparison, the creep test results also followed previous creep test studies.[2] The exception here being inconsistent performances in submerged creep tests by the representative epoxy adhesives.

From overall comparisons of pullout and creep test results, Adhesive A and Adhesive B (representative epoxy products) failed to exhibit capabilities for providing acceptable bonding of anchor installations under submerged conditions. Therefore, Adhesives C or E should be used for such applications. For dry

1 Ibid.

2 Best and McDonald, op. cit.

anchor installations, maximum design loads should not exceed the tensile loading capacity of the selected adhesive corresponding to test results for 0.254-cm (0.1-in.) anchor displacements.

Recommendations

The scope of this test study was limited to determinations of bonding capacities provided by various adhesives in accordance with established manufacturers' guidelines for product applications. However, in actual field applications, other parameters for anchor installations are commonly required. Some of these parameters play a significant role in the bonding performances for anchor installations including substrate temperature, anchor type, depth of hole, etc. Therefore, a test study comprising additional anchor installation parameters is recommended to provide comparative results for practical applications.

Appendix A
Pullout Test Results
Tables A1 - A8

Table A1
Pullout Test Results - Adhesive A - Dry Installations

Age, days		Load, kips 0.1-in. Displacements	Load, kips 0.2-in. Displacements	Load, kips Maximum
Dry Installations				
1		21.0	21.6	21.6
1		18.7	*	19.7
1		26.3	*	26.4
	Avg.	22.0		22.5
3		29.0	32.5	40.4
3		29.0	32.7	39.8
3		29.9	32.8	37.3
	Avg.	29.3	32.7	39.2
7		28.6	32.0	44.9
7		20.6	23.6	26.6
7		29.8	32.7	40.8
	Avg.	26.3	29.4	37.4
28		29.1	33.0	41.2
28		28.1	31.1	45.7
28		27.7	29.8	33.4
	Avg.	28.3	31.3	40.1
365		30.2	32.1	47.5
365		28.7	31.6	39.5
365		31.5	36.0	42.2
	Avg.	30.1	33.2	43.1

* Maximum load attained prior to displacement value.

Table A2
Pullout Test Results - Adhesive A - Submerged Installations

Age, days		Load, kips 0.1-in. Displacements	0.2-in. Displacements	Maximum
Submerged Installations				
1		2.7	5.2	9.1
1		3.5	6.2	8.1
1		4.4	7.3	9.5
	Avg.	3.5	6.2	8.9
3		0.9	1.7	2.4
3		1.5	2.1	2.5
3		4.9	5.7	10.1
	Avg.	2.4	3.2	5.0
7		2.1	3.3	7.3
7		3.8	7.6	17.2
7		2.6	3.8	7.3
	Avg.	2.8	4.9	10.6
28		6.4	10.7	15.1
28		2.7	5.4	11.9
28		7.0	10.7	17.8
	Avg.	5.4	8.9	14.9
365		10.2	13.6	19.1
365		10.4	15.1	19.4
365		10.1	13.4	16.4
	Avg.	10.2	14.0	18.3

Table A3
Pullout Test Results - Adhesive B - Dry Installations

Age, days		Load, kips 0.1-in. Displacements	0.2-in. Displacements	Maximum
Dry Installations				
1		27.9	28.1	28.3
1		29.8	32.8	33.2
1		29.0	31.4	32.7
	Avg.	28.9	30.7	31.4
3		29.2	32.8	46.1
3		23.6	23.8	23.9
3		29.0	33.1	44.8
	Avg.	27.3	29.9	38.3
7		28.3	33.6	41.2
7		29.2	32.5	32.5
7		27.6	31.5	36.2
	Avg.	38.4	32.5	36.6
28		30.1	32.6	41.7
28		28.0	31.2	45.4
28		29.3	32.7	34.8
	Avg.	29.1	32.1	40.6
365		29.3	31.1	43.3
365		29.1	32.2	48.1
365		29.3	32.0	34.2
	Avg.	29.2	31.8	41.9

Table A4
Pullout Test Results - Adhesive B - Submerged Installations

Age, days		Load, kips		
		0.1-in. Displacements	0.2-in. Displacements	Maximum
Submerged Installations				
1		2.7	5.8	16.9
1		2.3	4.1	16.3
1		1.3	1.9	3.4
	Avg.	2.1	3.9	12.2
3		3.1	3.9	5.8
3		15.9	21.3	29.4
3		4.9	8.7	17.8
	Avg.	8.0	11.3	17.7
7		14.3	18.6	21.6
7		4.5	7.7	18.3
7		5.3	9.4	20.1
	Avg.	8.0	11.9	20.0
28		13.1	16.9	31.2
28		6.4	9.8	28.9
28		4.8	7.0	23.0
	Avg.	8.1	11.2	27.7
365		10.5	15.0	27.0
365		18.0	27.9	30.4
365		12.2	21.0	30.6
	Avg.	13.6	21.3	29.3

Table A5
Pullout Test Results - Adhesive C - Dry Installations

Age, days		Load, kips 0.1-in. Displacements	0.2-in. Displacements	Maximum
Dry Installations				
1		28.5	31.5	46.6
1		28.4	32.5	46.0
1		29.8	33.6	46.5
	Avg.	28.9	32.5	46.4
3		28.2	30.7	46.1
3		28.1	30.2	46.3
3		29.0	31.6	46.4
	Avg.	28.4	30.8	46.3
7		28.3	30.1	46.2
7		28.9	31.7	46.8
7		29.4	32.9	46.9
	Avg.	28.9	31.6	46.6
28		28.7	32.0	42.5
28		28.7	32.0	47.1
28		28.5	31.8	43.8
	Avg.	28.6	31.9	44.5
365		29.6	32.4	42.6
365		30.1	39.2	46.3
365		29.6	32.3	44.3
	Avg.	29.8	34.6	44.4

* Maximum load attained prior to displacement value.
** Average of two anchor specimens.

Table A6
Pullout Test Results - Adhesive C - Submerged Installations

Age, days		Load, kips: 0.1-in. Displacements	Load, kips: 0.2-in. Displacements	Load, kips: Maximum
Submerged Installations				
1		19.0	22.0	24.7
1		22.3	23.6	26.4
1		28.5	30.4	30.4
	Avg.	23.3	25.3	27.2
3		26.7	29.1	29.7
3		28.6	28.6	29.9
3		16.8	18.2	21.4
	Avg.	28.4	25.7	27.0
7		18.7	*	19.3
7		23.1	26.7	30.5
7		25.1	*	26.3
	Avg.	22.3		25.4
28		24.9	*	25.1
28		25.0	*	25.5
28		25.1	*	25.5
	Avg.	22.3		25.4
365		29.2	30.5	32.4
365		26.2	*	26.2
365		28.6	29.5	30.3
	Avg.	28.0	30.0**	29.6

* Maximum load attained prior to displacement value.
* Average of two anchor specimens.

Table A7
Pullout Test Results - Adhesive D - Dry Installations

Age, days		Load, kips 0.1-in. Displacements	0.2-in. Displacements	Maximum
Dry Installations				
1		26.7	30.6	40.0
1		28.3	31.9	42.1
1		28.1	30.5	31.1
	Avg.	27.7	31.0	37.3
3		26.0	26.4	30.9
3		29.5	34.0	40.2
3		30.9	34.4	45.2
	Avg.	28.8	31.6	38.8
7		24.0	26.5	30.3
7		20.3	26.3	30.0
7		28.9	30.0	32.5
	Avg.	24.4	27.6	32.5
28		16.6	24.7	34.2
28		25.7	27.0	37.0
28		26.4	27.6	35.2
	Avg.	22.9	26.4	35.5
365		6.4	10.8	15.1
365		2.7	5.4	12.0
365		7.0	10.7	17.7
	Avg.	5.4	8.7	14.9

Table A8
Pullout Test Results - Adhesive E - Submerged Installations

Age, days		Load, kips 0.1-in. Displacements	0.2-in. Displacements	Maximum
		Dry Installations		
1		27.7	29.1	41.4
1		27.5	28.9	41.1
1		27.6	29.4	40.0
	Avg.	27.6	29.1	40.8
3		27.7	28.6	41.1
3		23.9	24.2	31.3
3		23.8	23.9	34.0
	Avg.	27.5	25.6	34.8
7		27.2	28.8	35.2
7		28.0	28.6	35.0
7		27.4	28.0	34.2
	Avg.	27.5	28.5	34.8
28		26.4	27.4	36.6
28		26.7	27.7	39.7
28		26.4	27.5	49.9
	Avg.	26.5	27.5	42.1
365		*	*	20.4
365		25.8	26.4	32.2
365		10.9	13.8	15.7
	Avg.	18.4**	20.1**	22.7

* Maximum load attained prior to displacement value.
** Average of two anchor specimens.

Appendix B
Creep Test Results
Tables B1 - B7

Table B1
Creep Test Results - Adhesive A - Dry Installations

Dry Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
1 day	0.0000	0.0000	0.0000	0.0000
1.125 days	0.0001	0.0000	0.0001	0.0001
4 days	0.0001	0.0000	0.0001	0.0001
5 days	0.0001	0.0000	0.0001	0.0001
6 days	0.0001	0.0000	0.0001	0.0001
8 days	0.0002	0.0000	0.0001	0.0001
11 days	0.0003	0.0000	0.0001	0.0001
12 days	0.0003	0.0000	0.0001	0.0001
13 days	0.0003	0.0000	0.0001	0.0001
15 days	0.0003	0.0000	0.0001	0.0001
19 days	0.0003	0.0000	0.0002	0.0002
22 days	0.0004	0.0000	0.0004	0.0003
25 days	0.0004	0.0000	0.0004	0.0003
29 days	0.0004	0.0000	0.0004	0.0003
33 days	0.0004	0.0000	0.0004	0.0003
34 days	0.0004	0.0000	0.0004	0.0003
36 days	0.0004	0.0000	0.0005	0.0003
39 days	0.0004	0.0000	0.0005	0.0003
43 days	0.0003	0.0000	0.0005	0.0003
46 days	0.0003	0.0001	0.0005	0.0003
50 days	0.0003	0.0001	0.0005	0.0003
53 days	0.0003	0.0001	0.0005	0.0003
56 days	0.0004	0.0001	0.0005	0.0003

(Continued)

Table B1 (Concluded)

Dry Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
64 days	0.0001	0.0001	0.0005	0.0002
70 days	0.0001	0.0001	0.0005	0.0002
77 days	0.0001	0.0001	0.0005	0.0002
85 days	0.0001	0.0001	0.0005	0.0002
92 days	0.0001	0.0001	0.0005	0.0002
99 days	0.0002	0.0001	0.0007	0.0003
105 days	0.0002	0.0001	0.0009	0.0004
120 days	0.0002	0.0002	0.0009	0.0004
139 days	0.0003	0.0003	0.0007	0.0004
158 days	0.0003	0.0003	0.0009	0.0005
183 days	0.0004	0.0003	0.0009	0.0005

Table B2
Creep Test Results - Adhesive A - Submerged Installations

Submerged Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
1 day	0.0156	0.0105	0.0103	0.0121
2 days	0.0272	0.0152	0.0134	0.0186
5 days	0.0303	----	0.0171	0.0237
7 days	0.0303	----	0.0180	0.0242
13 days	0.0303	----	0.0179	0.0241
15 days	0.0561	----	0.0179	0.0370
17 days	0.0572	----	0.0177	0.0375
19 days	0.0563	----	0.0177	0.0370
21 days	0.0564	----	0.0177	0.0371
27 days	0.0564	----	0.0177	0.0371
31 days	0.0564	----	0.0177	0.0371
34 days	0.0564	----	0.0177	0.0371
37 days	0.0564	----	0.0177	0.0371
51 days	0.0564	----	0.0177	0.0371
58 days	0.0564	----	0.0177	0.0371
68 days	0.0564	----	0.0178	0.0371
75 days	0.0565	----	0.0178	0.0372
83 days	0.0564	----	0.0178	0.0371
88 days	0.0564	----	0.0179	0.0372
96 days	0.0564	----	0.0179	0.0372
104 days	0.0564	----	0.0179	0.0372
116 days	0.0564	----	0.0179	0.0372
125 days	0.0571	----	0.0179	0.0375

(Continued)

Table B2 (Concluded)

Submerged Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
136 days	0.0578	----	0.0179	0.0379
142 days	0.0578	----	0.0180	0.0379
159 days	0.0578	----	0.0180	0.0379
163 days	0.0578	----	0.0182	0.0380

Table B3
Creep Test Results - Adhesive B - Dry Installations

Dry Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
1 day	0.0075	0.0051	0.0054	0.0060
1.125 days	0.0076	0.0054	0.0053	0.0061
4 days	0.0121	0.0081	0.0088	0.0096
5 days	0.0129	0.0086	0.0094	0.0103
6 days	0.0138	0.0092	0.0100	0.0110
8 days	0.0148	0.0100	0.0107	0.0118
11 days	0.0166	0.0111	0.0122	0.0133
12 days	0.0170	0.0110	0.0128	0.0136
13 days	0.0175	0.0117	0.0134	0.0142
15 days	0.0184	0.0122	0.0136	0.0147
19 days	0.0200	0.0135	0.0152	0.0162
22 days	0.0210	0.0153	0.0168	0.0177
25 days	0.0219	0.0150	0.0178	0.0182
29 days	0.0229	0.0163	0.0188	0.0193
33 days	0.0239	0.0163	0.0198	0.0200
34 days	0.0243	0.0166	0.0202	0.0204
36 days	0.0246	0.0169	0.0206	0.0207
39 days	0.0252	0.0173	0.0212	0.0212
43 days	0.0261	0.0178	0.0220	0.0220
46 days	0.0267	0.0181	0.0226	0.0225
50 days	0.0274	0.0186	0.0232	0.0231
53 days	0.0279	0.0188	0.0235	0.0234
56 days	0.0284	0.0191	0.0241	0.0239

(Continued)

Table B3 (Concluded)

Dry Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
64 days	0.0298	0.0198	0.0255	0.0250
70 days	0.0304	0.0203	0.0265	0.0257
77 days	0.0304	0.0206	0.0271	0.0260
85 days	0.0304	0.0217	0.0278	0.0266
92 days	0.0310	0.0223	0.0285	0.0273
99 days	0.0317	0.0228	0.0291	0.0279
105 days	0.0296	0.0233	0.0299	0.0276
120 days	0.0341	0.0245	0.0312	0.0299
139 days	0.0355	0.0256	0.0312	0.0308
158 days	0.0365	0.0261	0.0330	0.0319
183 days	0.0374	0.0270	0.0336	0.0327

Table B4
Creep Test Results - Adhesive C - Dry Installations

Dry Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
1 day	0.0015	0.0011	0.0016	0.0014
1.125 days	0.0016	0.0014	0.0016	0.0015
4 days	0.0020	0.0021	0.0018	0.0020
5 days	0.0020	0.0021	0.0018	0.0020
6 days	0.0021	0.0024	0.0020	0.0022
8 days	0.0021	0.0024	0.0020	0.0022
11 days	0.0023	0.0025	0.0022	0.0023
12 days	0.0023	0.0025	0.0023	0.0024
13 days	0.0024	0.0025	0.0023	0.0024
15 days	0.0025	0.0027	0.0025	0.0026
19 days	0.0026	0.0028	0.0025	0.0026
22 days	0.0027	0.0028	0.0026	0.0027
25 days	0.0028	0.0028	0.0026	0.0027
29 days	0.0029	0.0029	0.0026	0.0028
33 days	0.0029	0.0030	0.0026	0.0028
34 days	0.0030	0.0031	0.0027	0.0029
36 days	0.0030	0.0032	0.0027	0.0030
39 days	0.0030	0.0032	0.0027	0.0030
43 days	0.0030	0.0034	0.0028	0.0031
46 days	0.0031	0.0035	0.0028	0.0031
50 days	0.0031	0.0036	0.0028	0.0032
53 days	0.0031	0.0035	0.0029	0.0034
56 days	0.0032	0.0039	0.0030	0.0034

(Continued)

Table B4 (Concluded)

Dry Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
64 days	0.0032	0.0040	0.0032	0.0035
70 days	0.0033	0.0040	0.0032	0.0035
77 days	0.0033	0.0041	0.0033	0.0036
85 days	0.0033	0.0043	0.0034	0.0037
92 days	0.0034	0.0044	0.0034	0.0037
99 days	0.0034	0.0045	0.0035	0.0038
105 days	0.0035	0.0047	0.0036	0.0039
120 days	0.0035	0.0047	0.0038	0.0040
139 days	0.0035	0.0041	0.0040	0.0039
158 days	0.0036	0.0044	0.0041	0.0040
183 days	0.0036	0.0056	0.0043	0.0045

Table B5
Creep Test Results - Adhesive C - Submerged Installations

Submerged Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
1 day	0.0040	0.0022	0.0039	0.0034
2 days	0.0056	0.0031	0.0061	0.0050
5 days	0.0065	0.0039	0.0075	0.0060
7 days	0.0069	0.0042	0.0083	0.0065
13 days	0.0078	0.0046	0.0094	0.0073
15 days	0.0079	0.0047	0.0100	0.0075
17 days	0.0082	0.0050	0.0105	0.0079
19 days	0.0085	0.0050	0.0108	0.0080
21 days	0.0091	0.0050	0.0107	0.0083
27 days	0.0090	0.0051	0.0124	0.0088
31 days	0.0091	0.0052	0.0125	0.0089
34 days	0.0086	0.0052	0.0128	0.0089
37 days	0.0086	0.0053	0.0129	0.0089
45 days	0.0086	0.0055	0.0135	0.0092
51 days	0.0086	0.0056	0.0137	0.0093
58 days	0.0086	0.0056	0.0137	0.0093
68 days	0.0089	0.0058	0.0141	0.0096
75 days	0.0089	0.0060	0.0141	0.0097
83 days	0.0089	0.0061	0.0141	0.0097
88 days	0.0089	0.0060	0.0142	0.0097
96 days	0.0089	0.0060	0.0143	0.0097
104 days	0.0089	0.0060	0.0143	0.0097
110 days	0.0089	0.0060	0.0146	0.0098
116 days	0.0089	0.0062	0.0152	0.0101

(Continued)

Table B5 (Concluded)

Submerged Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
125 days	0.0093	0.0063	0.0154	0.0103
136 days	0.0096	0.0095	0.0154	0.0115
142 days	0.0096	0.0096	0.0154	0.0116
159 days	0.0098	0.0096	0.0154	0.0116
163 days	0.0098	0.0096	0.0154	0.0116

Table B6
Creep Test Results - Adhesive D -- Dry Installations

Age	Dry Installations			
	Deflection, in. (10,560 lb)			
	Spec. 1	Spec. 2	Spec. 3	Average
1 day	0.0025	0.0023	0.0023	0.0024
1.125 days	0.0028	0.0025	0.0026	0.0026
4 days	0.0039	0.0032	0.0039	0.0037
5 days	0.0040	0.0033	0.0040	0.0038
6 days	0.0043	0.0035	0.0042	0.0040
8 days	0.0045	0.0036	0.0044	0.0042
11 days	0.0049	0.0038	0.0047	0.0045
12 days	0.0049	0.0038	0.0047	0.0045
13 days	0.0051	0.0038	0.0048	0.0046
15 days	0.0052	0.0040	0.0049	0.0047
19 days	0.0053	0.0040	0.0050	0.0048
22 days	0.0054	0.0041	0.0051	0.0049
25 days	0.0055	0.0042	0.0051	0.0049
29 days	0.0055	0.0043	0.0051	0.0050
33 days	0.0056	0.0044	0.0052	0.0053
34 days	0.0056	0.0044	0.0053	0.0051
36 days	0.0056	0.0044	0.0053	0.0051
39 days	0.0056	0.0044	0.0053	0.0051
43 days	0.0059	0.0045	0.0054	0.0053
46 days	0.0059	0.0045	0.0054	0.0053
50 days	0.0059	0.0045	0.0054	0.0053
53 days	0.0060	0.0046	0.0054	0.0053
56 days	0.0060	0.0046	0.0055	0.0054

(Continued)

Table 6 (Concluded)

Dry Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
64 days	0.0061	0.0047	0.0055	0.0054
70 days	0.0062	0.0048	0.0055	0.0055
77 days	0.0062	0.0048	0.0055	0.0055
85 days	0.0063	0.0049	0.0056	0.0056
92 days	0.0064	0.0049	0.0056	0.0056
99 days	0.0064	0.0049	0.0055	0.0056
105 days	0.0064	0.0050	0.0056	0.0057
120 days	0.0067	0.0052	0.0055	0.0058
139 days	0.0068	0.0053	0.0056	0.0059
158 days	0.0062	0.0053	0.0057	0.0057
183 days	0.0065	0.0054	0.0059	0.0059

Table B7
Creep Test Results - Adhesive E - Submerged Installations

Submerged Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
1 day	0.0000	0.0004	0.0001	0.0002
2 days	0.0002	0.0009	0.0003	0.0005
5 days	0.0004	0.0014	0.0004	0.0008
7 days	0.0004	0.0015	0.0005	0.0008
13 days	0.0005	0.0015	0.0005	0.0008
15 days	0.0006	0.0016	0.0005	0.0008
17 days	0.0005	0.0016	0.0004	0.0008
19 days	0.0006	0.0016	0.0004	0.0009
21 days	0.0006	0.0015	0.0004	0.0008
27 days	0.0006	0.0018	0.0004	0.0009
31 days	0.0007	0.0018	0.0004	0.0010
34 days	0.0008	0.0017	0.0004	0.0010
37 days	0.0007	0.0018	0.0004	0.0010
45 days	0.0008	0.0018	0.0004	0.0010
51 days	0.0008	0.0018	0.0008	0.0011
58 days	0.0008	0.0018	0.0008	0.0011
68 days	0.0015	0.0019	0.0008	0.0014
75 days	0.0017	0.0018	0.0008	0.0014
83 days	0.0020	0.0018	0.0008	0.0015
88 days	0.0020	0.0018	0.0008	0.0015
96 days	0.0020	0.0018	0.0008	0.0015
104 days	0.0020	0.0018	0.0008	0.0015
110 days	0.0023	0.0018	0.0012	0.0018
116 days	0.0030	0.0018	0.0012	0.0020

(Continued)

Table B7 (Concluded)

Submerged Installations				
	Deflection, in. (10,560 lb)			
Age	Spec. 1	Spec. 2	Spec. 3	Average
125 days	0.0031	0.0020	0.0012	0.0021
136 days	0.0038	0.0020	0.0012	0.0023
142 days	0.0040	0.0020	0.0012	0.0024
159 days	0.0040	0.0020	0.0012	0.0024
163 days	0.0040	0.0021	0.0012	0.0024

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13. ABSTRACT *(Maximum 200 words)*

Rehabilitation of civil works hydraulic concrete structures such as navigation locks or stilling basins commonly involves the removal of defective concrete and replacement with new concrete. Steel reinforcing anchors are normally embedded into the base concrete to assist in the attachment of the base concrete to the new concrete. With respect to bonding the steel anchors into the base concrete, this investigation was conducted to evaluate the effectiveness of cementitious, vinylester and epoxy grouts in bonding embedment of the anchors. Tensile pullout and long-term creep strain tests were accomplished in this study in correlation with parameters for dry and wet environments and for bond maturity ages of 1, 3, 7, and 28 days and 1 year.

Tests results indicated all of the grout materials developed sufficient bond strength in pullout and creep tests for dry applications, with the exception of one epoxy material. However, for submerged applications, the epoxy grouts exhibited poor developed bond strength in both pullout and creep tests. As a result, particular caution is recommended for the application of epoxy grouts to embed steel anchors in hardened concrete under submerged conditions.

14. SUBJECT TERMS

Cementitious grouts	Hardened concrete	Reinforcement steel anchors
Chemical grouts	Polyester grouts	Underwater
Creep tests	Pullout tests	
Epoxy grouts	Rehabilitation structures	

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